GIOVE-B Chilbolton In-Orbit Test

Initial Results from the Second Galileo Satellite

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Antenna at Chilbolton Observatory, UK

ESA/RAL photo

Earlier this year, Galileo's second experimental satellite reached orbit and began broadcasting a wide range of signals, including the first transmissions of the new composite BOC signal on the L1 frequency. This article provides an initial report of GIOVE-B observations performed at the Chilbolton Observatory in the United Kingdom, which confirm the basic soundness of the prototype Galileo navigation signals.

The second Galileo In-Orbit Validation Element satellite, GIOVE-B, was launched from the Baikonour cosmodrome in Kazakhstan on April 27, 2008. Its main mission objectives are to maintain frequency filing, provide in-orbit validation of the Galileo payload units, specifically the passive hydrogen maser (PHM) and solid-state power amplifiers (SSPAs) that were not flown on GIOVE-A, measure the middle earth orbit (MEO) radiation environment, and continue signal-in-space (SIS) experimentation.

GIOVE-B's signals in space are fully representative of the operational Galileo system in terms of radio frequency and modulations, as well as chip rates and data rates. Before the launch, GIOVE-B's signal generator was upgraded to accommodate the MBOC (multiplexed binary offset carrier) modulation on the L1 signal. In fact, the first signal successfully transmitted by GIOVE-B was the composite BOC (CBOC) version of the MBOC signal. However, the navigation message currently being transmitted is not representative of the fully operational version from the perspective of structure and contents and is used for demonstration purposes only.

In addition to the main in-orbit test (IOT) station in Redu, Belgium, the European Space Agency (ESA) commissioned the Science and Technology Facilities Council (STFC) Chilbolton IOT station in the United Kingdom — which has been used for GIOVE-A commissioning and experimentation — to provide complementary measurements for GIOVE-B as well.

This article will present key results from the IOT campaign for GIOVE-B, primarily based on observations made at the Chilbolton station during May and June of this year.

Payload Operations

As with the first Galileo spacecraft, GIOVE-B first underwent platform

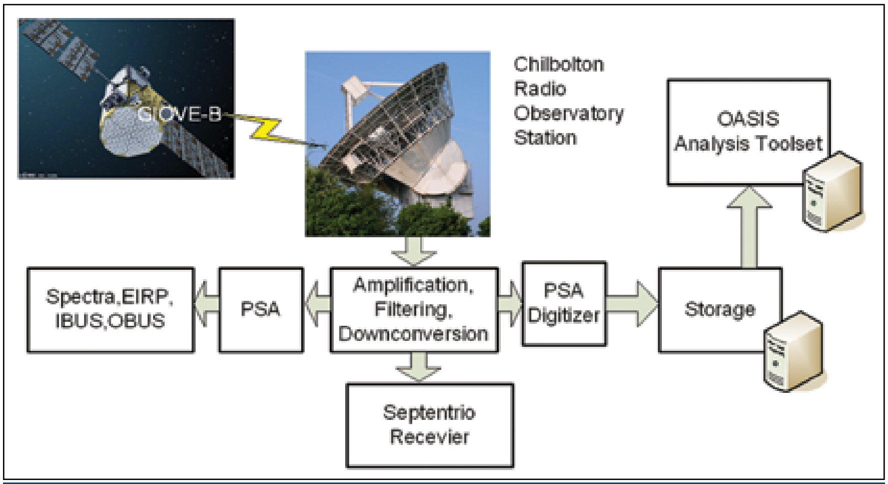

FIGURE 1 System for acquisition and analysis of GIOVE-B navigation signals at in-orbit test station, Chilbolton, UK

commissioning activities. In this phase, all the on-board systems undergo functional checks followed by the satellite's placement in its nominal Earth-pointing attitude and orbit control mode.

Following successful commissioning of the platform, the nominal payload units were switched on for the first time on May 5, with the first navigation signals transmitted early on May 7. The aim of the IOT campaign was to confirm that the payload functioned in orbit and that the operation of GIOVE-B's navigation signals was in line with the performance seen in ground tests completed before the spacecraft's launch.

During the May-June campaign, GIOVE-B transmitted a variety of signals with which controllers could check out various performance parameters over all three frequency bands: L1 (E1/E2), E5, and E6. We will describe these signals in greater detail later.

GIOVE-B has dual-redundant payload chains onboard. The first stage of the campaign was to test and fully characterize the nominal payload chain, followed by a reduced set of tests performed on the redundant payload to verify the key parameters. This article presents results for the nominal payload.

The default signals broadcast by GIOVE-B are L1 CBOC Interplex and E5 ALTBOC. These signals have been broadcast from the satellite since the end of the IOT campaign.

IOT Campaign

Prior to commencing the IOT measurement campaign, a number of system checks were carried out on the Chilbolton IOT station. These checks were designed to confirm that the station was operating nominally and that the performance was in line with the most recent full calibration test results. Another important part of the system check procedure was to perform an interference scan to identify any terrestrial interference sources. These results were referenced during the campaign if there were any unexpected spurious signals discovered in the GIOVE-B measurements.

Previous Galileo test campaigns have used a precision spectrum analyzer as the main measurement device. For the GIOVE-B campaign, a second similar device was installed to support the logging of large raw digitized data sets. An Off-Line Analysis of Signal-In-Space (OASIS) analysis tool set then used these digital samples to gain detailed insight into the signal spectrum envelope, modulation quality, time domain waveforms, code synchronism and correctness at the chip level, and correlation loss. Figure 1 shows the Chilbolton signal acquisition and analysis system.

Telespazio controllers in the Fucino ground station commanded GIOVE-B to broadcast a number of different signal modes during the in-orbit test campaign, which enabled a wide range of measurements to be taken. Table 1 shows the modulated and continuous wave (CW) signals transmitted and characterized during the IOT campaign and lists the corresponding key parameters measured. These in-orbit results were then compared with the ground tests, enabling ESA to confirm that the payload's performance had not been affected during the satellite's launch and insertion into orbit.

The GIOVE-B payload is capable of transmitting on two frequency bands simultaneously. Therefore, the modulated signals were always transmitted as part of a dual-frequency signal mode, either L1-E5 or L1-E6. In addition, a CW signal was broadcast in each frequency band to confirm the effective isotropic radiated power (EIRP) of the payload transmissions.

During each satellite pass dedicated to measuring the modulated signals, at least two spectral plots were taken of each signal being broadcast along with at least two full sweeps of the defined out-of-band spurious (OBUS) bands. Experience from previous IOT campaigns had highlighted the benefit of having two repeat measurements for each band of interest to help identify external inference sources.

EIRP and Received Power

Ideally, lengthier satellite transit paths should be assigned to the CW signals to enable the EIRP to be measured across a long cut through the antenna pattern. For all signals on the nominal payload, except E6 CW, two passes were dedicated to each CW signal to provide two different slices through the antenna pattern.

For users, probably the most relevant parameter of interest is the signal power they receive on the ground. This can be evaluated from the EIRP by subtracting the free space path loss (FSPL) experienced by the signals as they travel from the satellite to the user. Table 2 presents the minimum received power levels measured at Chilbolton for each CW signal transmitted by GIOVE-B.

These results were very much in line with the ground reference tests of GIOVE-B's hardware at both the spacecraft and payload levels throughout the life cycle of the spacecraft. For example, during thermal vacuum (TVAC) testing the spacecraft is placed inside a vacuum chamber and the temperature is varied to simulate the space environment.

CW Frequency

The center frequencies of the CW signals were measured by ESA at their Redu station. The relative motion of the spacecraft was estimated to remove the Doppler shift from the measurements. ESA's Redu results are summarized in Table 3. The measured results are in very good agreement with the expected center frequency values.

Spectral Plots, IBUS, and OBUS

Spectral plots were taken for every modulated signal to verify that the signals were being generated correctly. Figure 2 shows the L1 CBOC Interplex signal recorded at the Chilbolton station. As can be clearly seen, a slight asymmetry of around 1 dB appears in the BOC[15,2.5] major sidelobes. (Please note that the spur at 1600 MHz in the plot is from a known terrestrial interferer and is not being transmitted by the GIOVE-B payload.)

The relative 1 dB asymmetry seen in Figure 2 is due to both the contribution from the Chilbolton station itself and the transmitted signal. However, no fix has been needed for the signals from the GIOVE-B spacecraft as proven by the good receiver tracking performance.

Figure 3 contains similar spectral plots for the default modulated signals on the E5 and E6 frequency bands. The two spurs

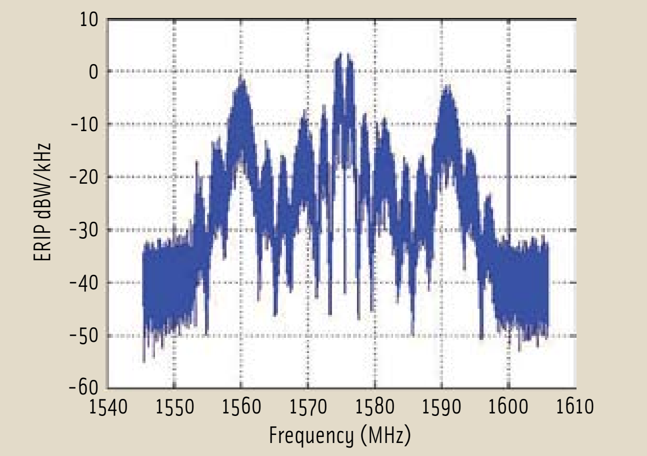

FIGURE 2 L1 CBOC interplex spectrum

Signal Type	Modulation	Measurements
Modulated signals	E5 ALTBOC [15,10] E6 Interplex {BOC[10,5],QPSK[5],QPSK[5]} E2L1E1 Interplex {BOC[15,2.5],BOC[1,1],BOC[1,1]} E2L1E1 CBOC {BOC[15,2.5],BOC[6,1], BOC[1,1],BOC[1,1]}	Spectral plots Occupied bandwidth Out-of-band spurious (OBUS) GIOVE receiver tracking Digitized data
CW signals	E5a CW E5b CW E6 CW E2L1E1 BOC[15,0] CW	EIRP In-band spurious (IBUS) Polarization purity Digitized data

TABLE 1. Modulations and key parameter measurements of GIOVE-B signals in space

Date	PL A	Expected (MHz)	Measured (MHz)	Delta (Hz)
14-05-08	L1 lower	1560.075000	1560.075044	44
14-05-08	L1 upper	1590.765000	1590.765044	44
19-05-08	E5a	1176.450000	1176.450032	32
20-05-08	E5b	1207.140000	1207.140032	32
26-05-08	E6	1278.750000	1278.750036	36

TABLE 3. Center frequency measurements recorded at ESA Redu station

Frequency	Minimum Received Power (dBW)
E2L1L1	-156.5
E5a	-152.1
E5b	-152.5
E6	-152.3

TABLE 2. Minimum received powers

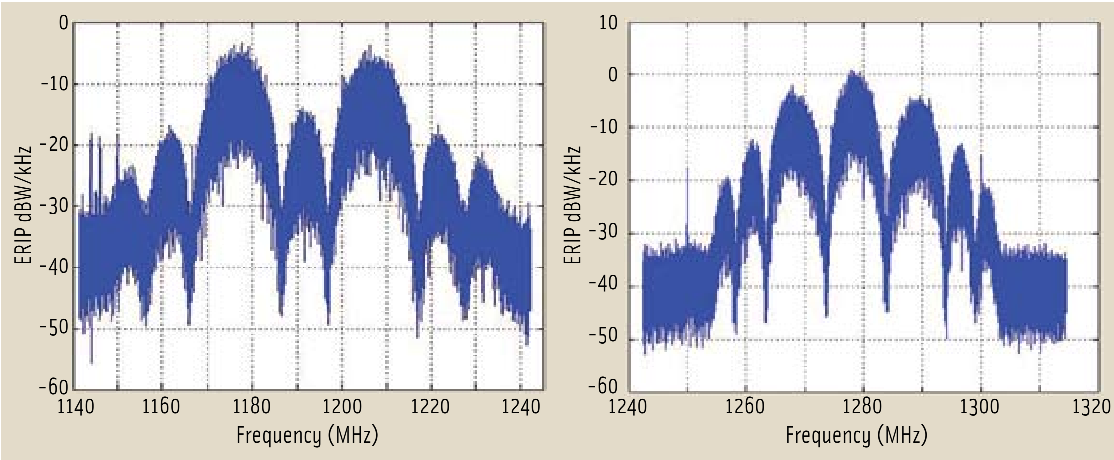

FIGURE 3 E5 ALTBOC and E6 Interplex spectra

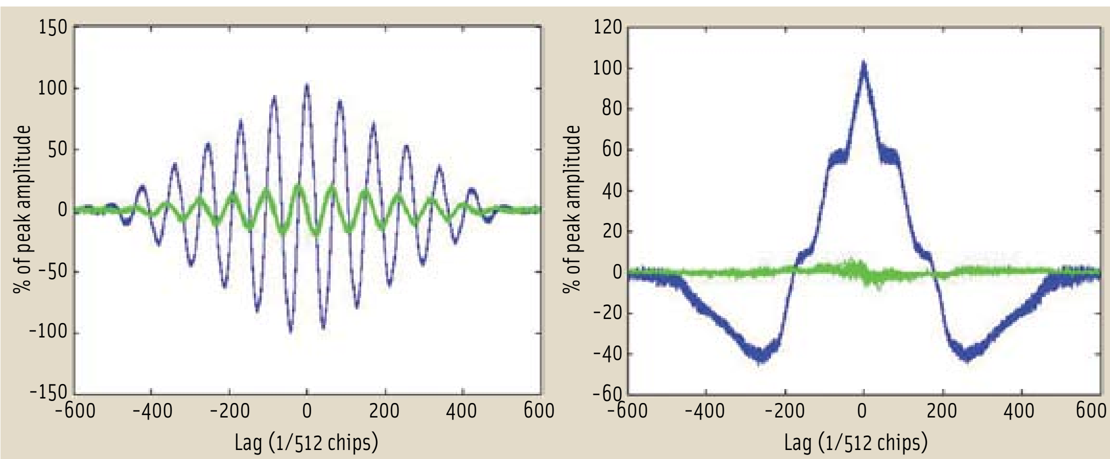

FIGURE 4 Auto-correlation functions for L1-A and L1-BC CBOC signal components

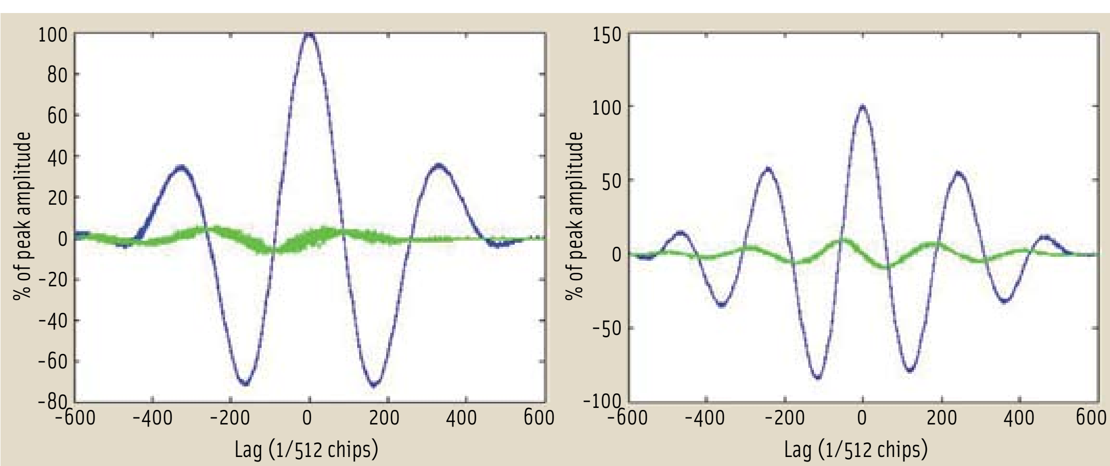

FIGURE 5 Auto-correlation functions for E5 ALTBOC and E6-A BOC signal components

at 1250 and 1300 MHz on the E6 plot are known terrestrial interferers. The noisy spurs at the lower end of the E5 band represent interference from distance measuring equipment (DME) transmitters at several airports in the vicinity of the Chilbolton station.

All spectral plots obtained during the IOT campaign compare well with the spectra measured during the reference ground tests. Similarly, an analysis of the IBUS for each of the CW signals detected no anomalies.

The OBUS bands investigated during IOT were limited by the receiving bandwidth of the Chilbolton station, which covers the RF spectrum from 1100 MHz to 1700 MHz. The noise floor of the Chilbolton measurements prohibited an in-depth investigation of spurious signals down to the level of the GIOVE-B specifications. Therefore, these in-orbit tests were limited to looking for gross errors in the transmissions. None of the OBUS results indicated any unexpected anomalies that could be attributed to the GIOVE-B payload.

Receiver Tracking

A GIOVE experimental receiver is installed in Chilbolton in a dual-mode configuration that enables the receiver to be connected either to the station's original 25-meter dish or to an omnidirectional antenna. During the IOT campaign the receiver was connected to the 25-meter dish to enable ESA to track the navigation signals with an excellent signal-to-noise ratio.

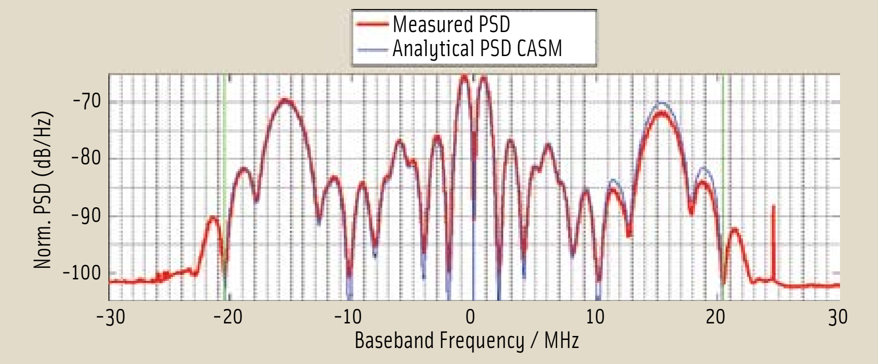

FIGURE 6 OASIS L1 CBOC Interplex Spectrum

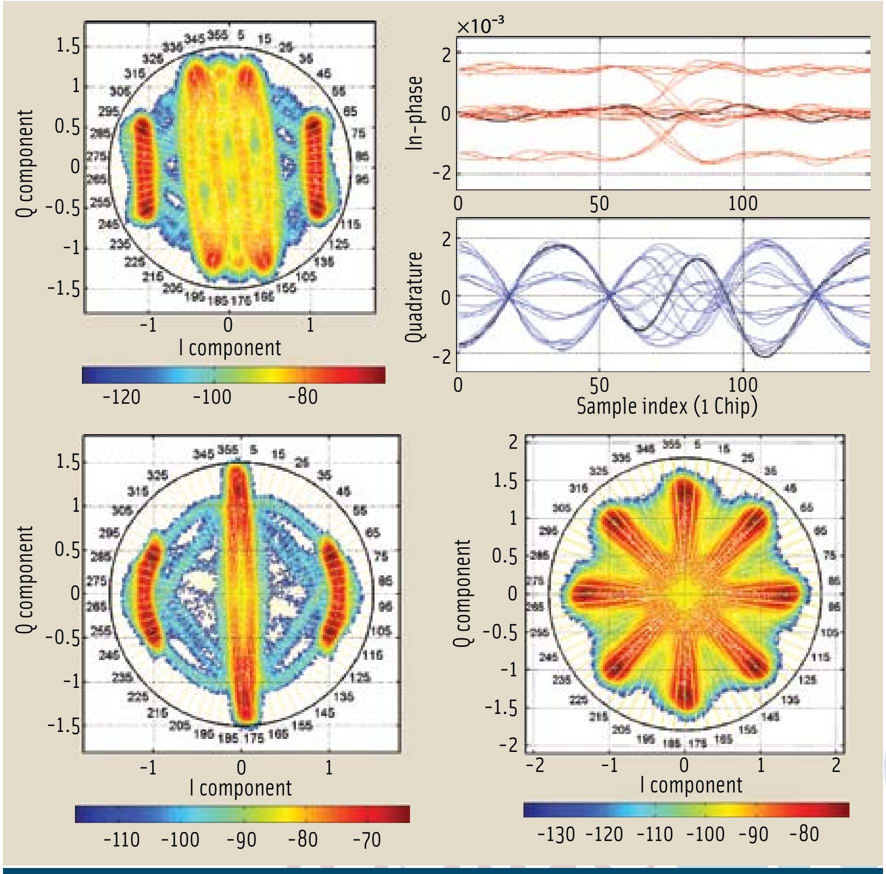

FIGURE 7 L1 CBOC (upper left), E6 Interplex (lower left), and E5 ALTBOC (lower right) phase states and L1 CBOC time domain plots (upper right)

For each modulated signal, including the new MBOC signals, the receiver was used to log both navigation and measurement data. In addition, the receiver can measure and record the auto-correlation functions (ACFs) of the signals. **Figure 4** presents the auto-correlation functions measured for the L1-A BOC(15,2.5)-C and L1-BC CBOC(6,1,1/11)-S signal components. **Figure 5** contains similar results for the E5 ALTBOC and E6-A BOC(10,5)-C signal components.

All ACFs measured on the signals transmitted in orbit were in line with the reference ground results. Please note that the L1-A BOC [15,2.5] ACF is symmetrical and, therefore, is easily tracked by the receiver.

OASIS Results

Off-Line analyses were performed on digitally sampled segments of the GIOVE-B navigation signal-in-space received by Chilbolton Station's high-gain antenna and compared with the "ideal" waveform of such signals. These were used to gain detailed insight into the signal spectrum envelope, modulation quality, time domain waveforms, code synchronism and correctness on the chip level, and correlation properties such as correlation loss and deviations from the "ideal" shape. In this section, we present selections of the results of the OASIS analysis.

Figure 6 shows the L1 CBOC interplex observed spectrum (red) against the ideal spectrum with equivalent power (blue). The default GIOVE-B configuration for L1 consists of L1-A using a BOCc(15,2.5) signal on the quadrature component, and L1-B/C using CBOC modulation with power sharing 1/11 for BOC(6,1) and 10/11 for BOC(1,1) on the in-phase component of the carrier.

A slight imbalance with decreasing amplitude towards higher frequencies appeared in the observations at Chilbolton. After removal of estimated contributions from the measurement station, the average imbalance is estimated to be on the order of magnitude of 1dB.

After baseband conversion, we can analyze the modulation quality, e.g., from scatter plots in the form of histograms as shown in **Figure 7**.

OASIS results for all the signal samples are encouraging and reinforce that fact that GIOVE-B is transmitting the expected navigation signals.

Future GIOVE-B IOT

Four repeat IOT campaigns are planned throughout the lifetime of the GIOVE-B mission. The satellite is designed to operate for 24 months following its commissioning and in-orbit test period. Therefore, the repeat campaigns will be nominally six months apart.

The aim of the campaigns is to assess the performance of the payload throughout the lifetime of the mission in order to verify that no degradation has occurred in the navigation signals. Each campaign will last for three weeks and will repeat key performance measurements for each of the main signals, namely the L1 CBOC Interplex, E5 ALTBOC and E6

Interplex modulated signals and each of the four CW signals.

Concluding Remarks

ESA coordinated an intensive in-orbit test campaign involving several IOT stations in the two months following the April 27 launch and early orbit phase and platform commissioning activities for GIOVE-B.

ESA used the Chilbolton IOT station to carry out complementary IOT measurements in parallel to the main IOT station at Redu. The performance of the measurement system at Chilbolton had been proven during earlier GIOVE-A IOT campaigns. As a result, the combined STFC/SSTL team, working in close collaboration with the ESA team, had already gained considerable experience in measuring and analyzing satellite navigation signals. The high quality of the measurements taken on the GIOVE-B signals at Chilbolton has been recognized by ESA.

The GIOVE-B satellite has now joined GIOVE-A in routine operations. With the exception of specific future IOT activities or spacecraft maintenance, both satellites are now continuously broadcasting prototype Galileo navigation signals that can be used for SIS experimentation purposes.

Acknowledgments

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Manufacturers

The precision spectrum analyzers used in the Chilbolton GIOVE-B tests were the E4440A from **Agilent Technologies, Inc.**, Santa Clara, California, USA. The Galileo receiver installed at the Chilbolton station is the GSTB-v2 Experimental Test Receiver (GETR) from **Septentrio Satellite Navigation**, Leuven, Belgium. The omnidirectional antenna at Chilbolton is the Galileo Ground Segment Reference antenna from **Space Engineering S.p.A.**, Rome, Italy.

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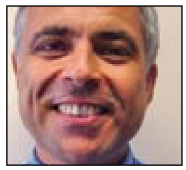

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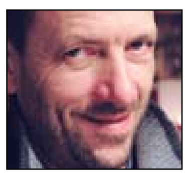

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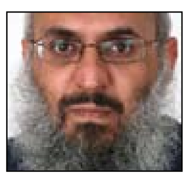

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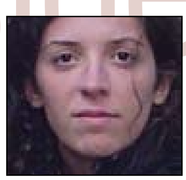

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