

# A New Approach To Real-Time Water-Vapour Wind Extraction

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*This user report describes scientific aims and user experience with a high-performance computer developed by GEPARD.*

The Fast Satellite Image Processing System (FESIP) consists of:

- CineSat - for high performance image display and analysis
- Online Meteosat image rectification; and
- Realtime wind field computation from image sequences

The graphic underscored in blue (see p. 112) gives an overview of the system developed by GEPARD. MF1 and MF2 indicate the two mainframe computers; the link is via FDDI-LAN in realtime. A brief description of the hardware modules is given in the text underscored in yellow on p. 113.

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## Introduction

Pre-operational meteorological activities were started at ESA's European Space Operations Centre (ESOC) with the launch of the first Meteosat satellite in November 1977. The complete Meteosat system became fully operational on 23 November 1983 and since then has provided the user community with all of the types of data required for reliable weather forecasting, including both pre-processed image data and derived meteorological products (cloud-motion vectors, sea-surface temperatures, upper-tropospheric humidity, cloud-top heights, etc.).

**The prototyping and subsequent validation of a new image-resampling technique have shown that the geometric stability of presently available satellite-derived meteorological data could be improved without having a negative impact on the radiometric quality. Initial results have already shown that 10% more wind vectors pass the quality-control tests thanks to the improved geometric stability of the imagery data. Additionally, it has been proven that the derived products can be produced in real time, i.e. on a half-hourly basis. This will increase Meteosat's economic benefits, particularly in areas where real-time information plays an important role, such as the prediction of hurricane development, and forecasting for aviation, road transportation and ship routing.**

In-orbit redundancy was achieved with the launch and successful commissioning of Meteosat-3 in June 1988. This satellite was the first of an improved design, with consumables for an operational lifetime of five years. This satellite launch was followed by several more, in the framework of the Meteosat Operational Programme, as shown in Figure 1.

As from July 1991, the Meteosat operations were extended by positioning one of the satellites at 50°W, thereby providing additional coverage of the Atlantic Ocean. This has subsequently been referred to as the Atlantic Data Coverage (ADC) mission. A later extension of the ground segment with the implementation of a Meteosat-compatible

ground station at Wallops (USA) enabled the ADC Meteosat satellite to be moved to an even more westerly position. The satellite is currently located at 75°W and is referred to as the 'Extended Atlantic Data Coverage (XADC) mission'.

Currently, ESA is still operating all of the Meteosats: the European operational system, positioned at 0° on behalf of Eumetsat, and the satellite positioned at 75°W on behalf of the US National Oceanographic and Atmospheric Administration (NOAA). By 30 November 1995, Eumetsat will have established its own operational capabilities for the Meteosat satellite(s) positioned at 0°.

ESA, being first and foremost a research and development organisation, will continue its role in satellite meteorology through its active development effort for the so-called 'second generation' of meteorological satellites. ESA-funded R&D efforts conducted as part of the present operational programme have already produced improvements in the radiometric accuracy and geometric stability of Meteosat imagery, as well as leading to the production of real-time derived products such as wind vectors. The results of some of these studies are reported here.

## Geometrical image compensation

Four images transmitted once every 30 min from each of the operational Meteosat spacecraft are received at ESOC in three spectral channels – the infrared window, water-vapour absorption band, and visible band (two images). Each of these images contains 2500 x 2500 pixels (2500 x 5000 for the visible channels), with 8 bits per pixel. Two such image data streams are currently processed in parallel at ESOC on one of two mainframe computers (Comparex 8/98's). The second mainframe serves as a backup, but is normally used for other purposes. These machines have been regularly upgraded to cope with the need



for ever-greater computing power, progressing from about 2 Mips in 1981 to over 50 Mips today.

The Meteosat images processed and disseminated by ESOC are used by a wide research community as a means of gaining a better understanding of atmospheric processes. Success in this respect, however, is highly dependent on the radiometric quality and geometric stability of the image data. The latter is achieved by applying a data-correction process called 'image rectification'. Images transmitted from the satellite are distorted due to its various movements during the image-

The resampling method initially selected was so-called 'nearest-neighbour resampling'. It was fast and cheap, as the computational requirements were minimal, but it caused a residual statistical error. This resulted in a degradation of the absolute accuracy of the data points, as well as their relative stability (Fig. 2). In this type of resampling, some pixels are taken twice, others are missed completely and the rectified images are characterised by a blocky appearance with random shifts of large areas in the image.

In recent years, the determination of the image deformation has been significantly improved,

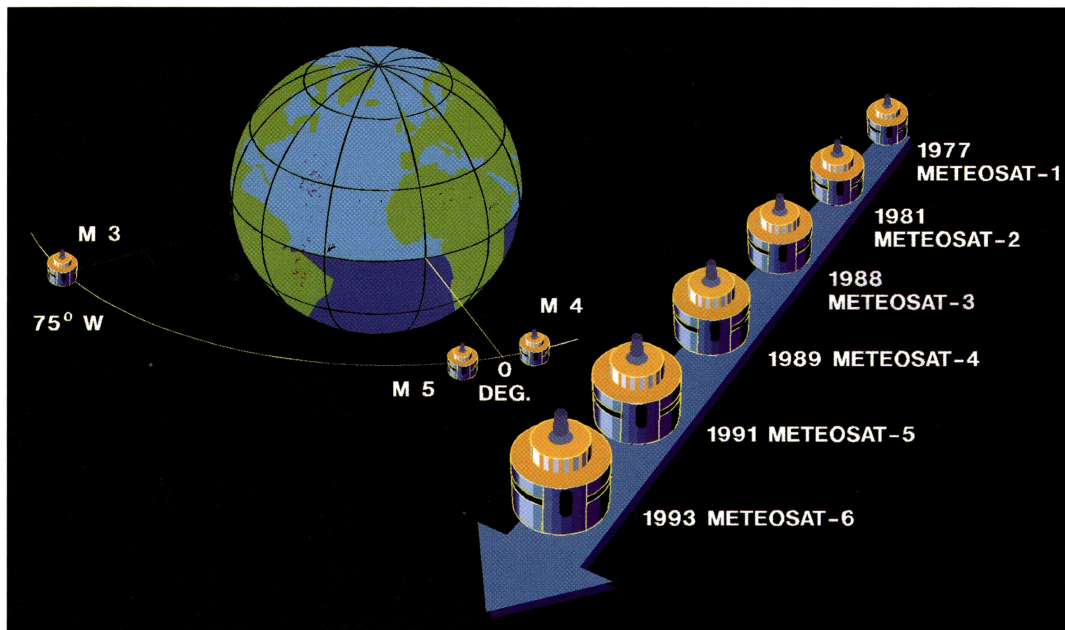


Figure 1. Meteosat launch scenario

taking process. Since this prevents an accurate geographical identification of an image pixel, an evaluation of the image distortions and a consequent resampling of the image pixels is one way of reducing these geometrical errors.

It has become possible in the last few years to perform raw-image rectification for Meteosat in real time. Three main steps are involved. First, a number of varying parameters of the imaging systems need to be determined. They can be partly predicted, because most of the disturbing forces affecting the spacecraft parameters are periodic in nature and are partly derived from real-time measurements. Based on these parameters, the deformations on a series of grid points are calculated using a mathematical model. Finally, the raw image pixels are resampled according to the resulting deformation matrix to form the rectified image.

such that the rectification errors averaged over an image are close to the theoretical minimum (in the absence of external perturbations such as eclipses). In order to improve the rectification quality still further, another resampling algorithm was needed to replace the original nearest-neighbour scheme.

A variety of methods were possible, all based on the interpolation of weighted-pixel counts

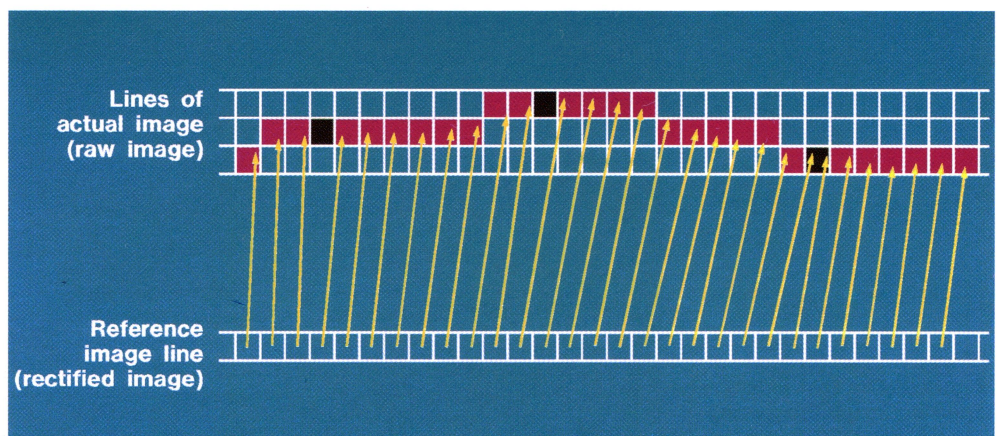


Figure 2. The principle of nearest-neighbour rectification



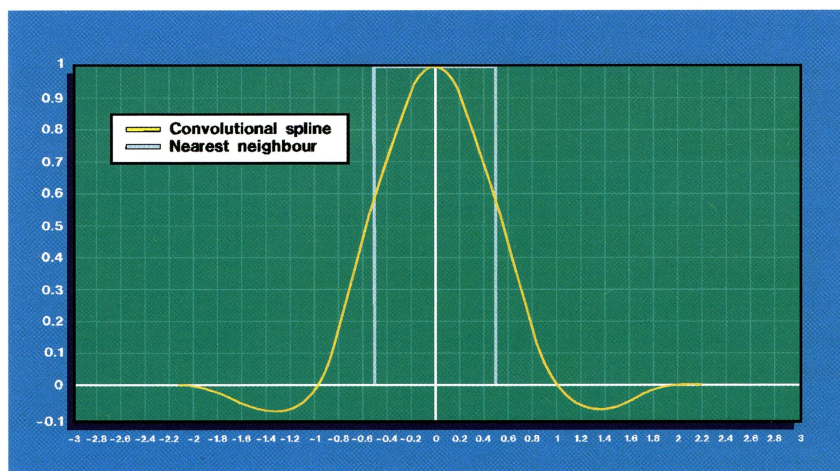


Figure 3. Pulse response functions

surrounding the pixel in question. Radiometric changes introduced in this way are well within the accuracy of the radiance figures themselves. They could even lead to an improvement by reducing the impact of the satellite's radiometer and associated equipment on the original image.

A study was initiated, using a software model of the sampling process of Meteosat's instrumentation and electronics together with on-ground sampling, to identify an optimal method for Meteosat image data resampling. Fourteen different resampling methods were tested. The most promising candidates (best behaviour for edges and smooth areas) were the bi-cubic spline function, a linear combination of B-splines, and the nonlinear Akima interpolation. All three methods showed significantly improved results compared with the nearest-

neighbour technique when applied to deformed test images in initial trials (Fig. 3).

### Real-time processing

The technical realisation of these very time-consuming resampling algorithms led to the development of a state-of-the-art transputer-augmented workstation (by the Austrian company GE.PAR.D) under ESA contract and with support from the Austrian government. The resulting Fast External Satellite Image Processing (FESIP) system is shown in Figure 4.

The scope of the contract was to develop a computer prototype (hardware and software) for the real-time resampling using the various interpolation techniques, product extraction, and rapid image display and processing. The FESIP prototype design supports interfaces to modules for further processing. Besides the rectification module, a second component is used for near-real-time data extraction. This module computes water-vapour wind vectors (WVWV) using an optimum pattern-matching algorithm. Various quality-control tools are then applied to the wind vectors, all with a minimum interaction with the present mainframe computer system.

### Wind-vector extraction

The wind-vector fields extracted from successive images of the different Meteosat channels are the most important products that are presently derived at the Meteorological Information Extraction Centre (MIEC) in ESOC.

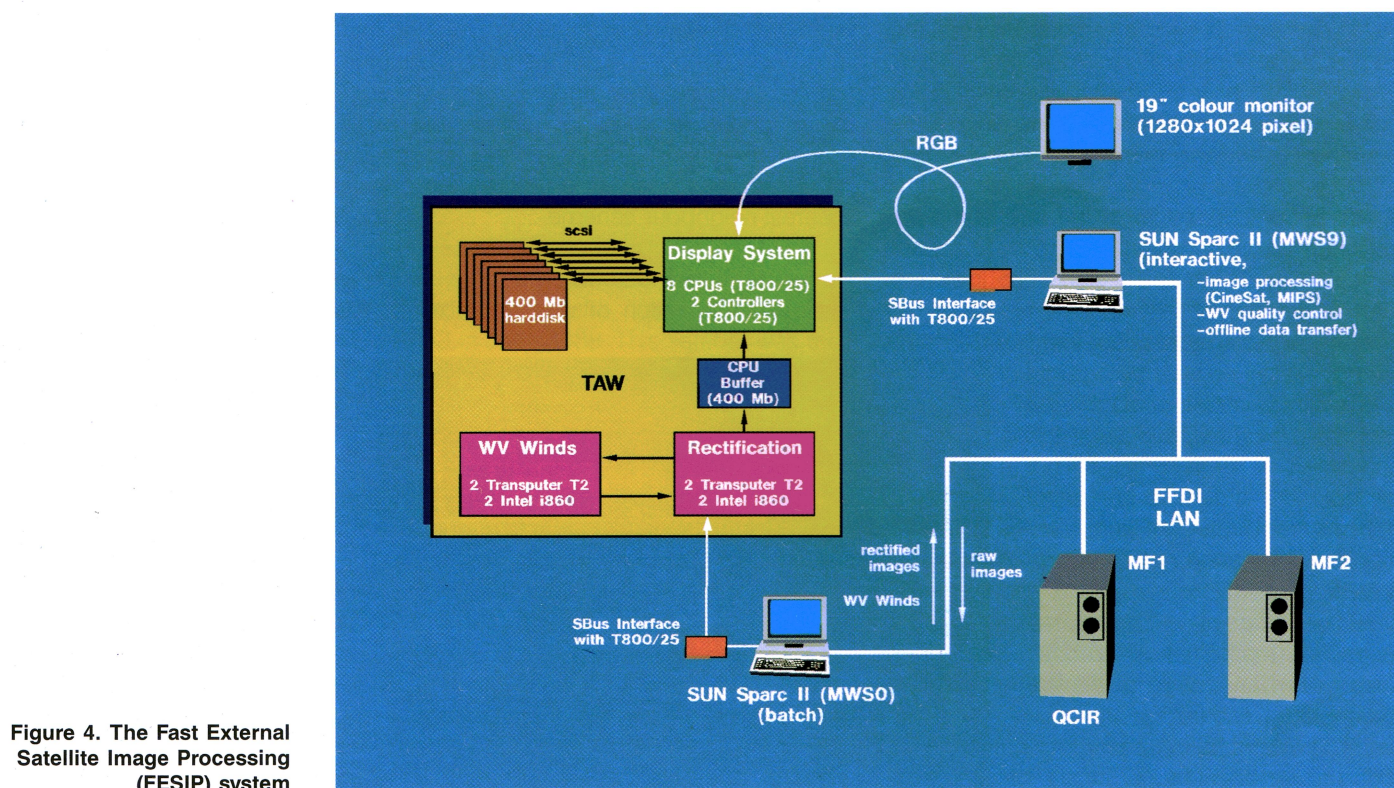


Figure 4. The Fast External Satellite Image Processing (FESIP) system



### The Transputer-Augmented Workstation

The TAW is equipped with a total of 23 Central Processing Units (CPUs), distributed across four different modules. Its formidable capacity is highlighted by the processing power of just one of these modules for real-time image-data resampling, which achieves a floating-point performance of almost 200 Mflops.

The main components of the TAW are the resampling and WVWV modules, both of which consist of a combination of T800 transputers and Intel i860 processors. These functions are controlled via a SunSparc host computer, which also performs the image-data transfer from and to the ESOC mainframes in batch mode. Raw and resampled images are also automatically transferred via a buffer module to the TAW's display system.

Eight hard disks with a total of 3.2 Gbyte of storage, each equipped with a dedicated transputer for fast I/O processing, are available to store these images in a cyclic file system. This allows fast and parallel zooming, scrolling and loops of up to 500 infrared images or 125 full-resolution visible-channel (VIS) images (5000 x 5000 image pixels) on a high-resolution monitor.

Additional functions of this module are pixel inspections, window extraction and grey-value statistics, classifications and Fourier Transformations, overlays, etc.

The new TAW's (see above) high processing capability enables near-real-time extraction of these vector fields on a half-hourly basis. This means that 48 vector fields can be produced daily compared with the four fields presently produced operationally.

For the derivation of the meteorological products, each Meteosat image is divided into 3560 segments. If one tries to produce a vector in each segment and for every possible displacement, 15 million matching operations are required which, regardless of the matching method, would require an inordinate number of computations.

In order to reduce the amount of computation, the TAW matching is performed in two steps. In the first step only every third matching is performed, while in the second step the steepest gradient for each point in the first step surface is followed to a local minimum. The final matching is the global minimum found from the set of local minima. Elaborate testing with a full-search implementation has shown that the true minimum is found in this way for more than 95% of all vectors.

In its present configuration, the TAW is geared to near-real-time vector derivation from Meteosat's water-vapour channel. This channel was chosen due to its ability to track not only cloud displacement, but also moisture movement. Moreover, due to the water-vapour channel's response function, the measured radiance always originates from the mid- or upper troposphere, usually from above a pressure level of 600 hPa, which in a standard

atmosphere is roughly equal to 4 km. This is especially important for several meteorological applications (see below).

The set of derived wind vectors are only useful if they can be assigned to an appropriate height. The TAW is capable of producing an 'Equivalent Black-Body Temperature' (EBBT), where the mean radiance of the coldest 25% of the pixels is converted into a temperature. If the atmospheric temperature distribution is known, the EBBT can then be related to a specific height.

In the typical WVWV field presented in Figure 5, it can be seen that the vector field is generally smooth. An important aspect for an automated derivation scheme is also revealed, however, in that some of the derived vectors do not follow true cloud or moisture patterns. They are a result of tracking noise or rapidly changing or evolving features but, as they do not contain any useful information, these vectors should be removed from the vector fields before the product is disseminated to the users. This is done by the automatic quality-control tool.

#### Automatic quality control (AQC)

Given the vast amount of data produced by the TAW, a manual quality-control scheme is out of the question. The only option is an automatic scheme capable of removing all odd winds. The solution adopted, which has evolved from the operational MIEC AQC scheme, supplements the existing MIEC features with many new ones. The TAW AQC implements three specific selection criteria that remove every



wind exceeding a specific type of threshold (e.g. a vector with a magnitude of more than 100 m/s is unlikely to be correct even in high-wind-speed regions of the atmosphere), and fifteen quality tests, the combined results of which permit a final quality evaluation of each individual vector.

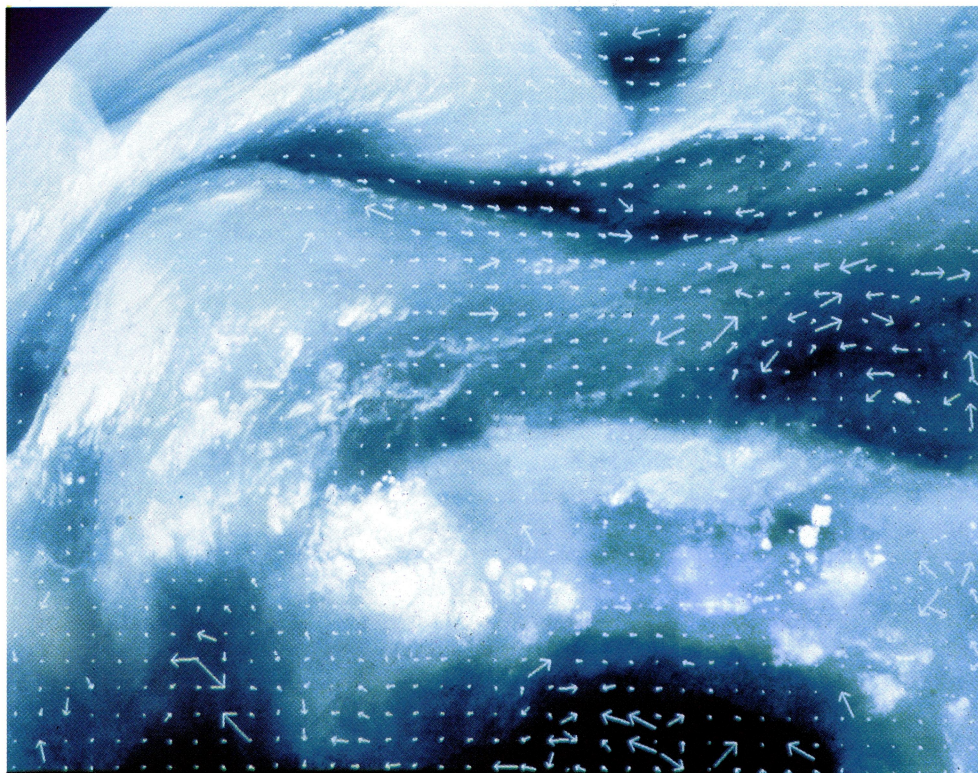
The TAW AQC tests are based on consistency in time and space, as well as on reliability

in which wind data derived from Meteosat's water-vapour channel are to be sent from the FESIP processing facility at ESOC in near-real time to the ECMWF in Reading, UK. The Cooperative Institute for Meteorological Satellite Studies (CIMSS) and NOAA/NESDIS in Madison, USA have also expressed interest in participating. Their intention would be to compare the ESOC water-vapour winds with the four-times daily snapshot of water-vapour winds produced operationally by NESDIS' with data from the Meteosat located at 75°.

The significance of this study is twofold. Firstly, the technological challenge of real-time processing including an automatic online quality-control feature represents the ultimate test bed for FESIP. Secondly, it will be the first time that satellite-derived winds of such high quality and frequency have been delivered in near real time to an operational forecasting centre. In addition, the ECMWF's excellent data-monitoring capabilities will be able to provide an independent assessment of the wind vectors produced, the quality control and the quality indicator attached to each vector.

In addition to the use of FESIP products in numerical weather prediction, we see a large potential for their use in scientific applications, which can also be elaborated as part of this measurement campaign. For example:

- (a) Radio-signal propagation through the Earth's atmosphere is affected by refraction. The corresponding excess propagation path varies with the total column water-vapour content. This so-called 'wet delay' is highly variable in space and time. The present work can contribute to the study of spatial variability of the 'wet delay'. A method has already been developed to infer the total column water vapour (TCW) from cloud-free infrared window radiances from Meteosat over sea. This product will be derived for a given Meteosat image by the FESIP station. The display will allow the identification of areas with maximum gradients. An overlay of the TCW product with the water-vapour winds provides a unique tool for estimating the displacement of areas with a high water-vapour content. Study of the spatial variability of the 'wet delay' would thus provide a quasi-global analysis including all climate zones over the oceans. It will



**Figure 5. A typical Water-Vapour Wind Vector (WVWV) field**

of the vector derivation and their height assignment. As the final vector quality is obtained as a weighted mean of all tests, the derivation of an optimum AQC configuration is rather complicated and so the TAW is equipped with an interactive tool to help in this task.

The interactive QC tool provides statistical information on the performance of any test or combination of tests. It allows the test configuration to be optimised until a setup is found that gives the best possible results.

#### **Validation campaign**

The TAW can provide wind fields derived from satellite images continuously for time intervals of 30 minutes. This information is extremely useful for the new analysis schemes for numerical weather prediction now being implemented at weather-forecasting centres.

The European Centre for Medium-Range Weather Forecasts (ECMWF) has already expressed a keen interest in running a one-month 'Real-Time Winds Validation Campaign'



be enhanced by the availability of displacement vectors, which can provide a quick means of forecasting a change in 'wet delay'.

- (b) The animation of vector fields and the estimation of trajectories could be important in 'nowcasting'.
- (c) An overlay of a cloud-analysis product will delineate 'pure water vapour' wind vectors from those derived from cloud tracking. The pure water-vapour winds have been shown to represent a mid-level wind field, which is indicative of the displacement of tropical storms and hurricanes.
- (d) A joint analysis of Upper Tropospheric Humidity (UTH) with wind fields provides insight into the dynamics of the upper troposphere and its relationship to the moisture field. This tool would have great potential in climate-related studies.

#### Potential use of real-time wind vectors

As indicated in the previous section, one of the main uses of real-time wind vectors is in numerical weather-prediction models. Until this year, most global models were only capable of assimilating data derived at the main observation times, i.e. with a six-hour time interval. Now these models can also assimilate data derived at intermediate times but, with the exception of a fairly small number of automatic weather stations, only geostationary satellites are capable of producing high-frequency observations of the atmosphere. Therefore, the half-hourly vector fields provide an excellent opportunity for the user community to assess their new schemes. Simultaneously, the quality of the WVWV could be assessed.

A further use of real-time water-vapour vectors is in the area of short-term weather prediction and nowcasting. In these areas, the data would not be used merely by the national meteorological services. A potentially large user community can be found in aviation, for example, for whom an accurate description of the current atmospheric state is an important flight-routing consideration. An optimum route ensures minimum fuel consumption, not only by taking any tail winds into account, but also because more accurate fuel-consumption estimating allows the extra load that would be constituted by carrying unnecessary excess fuel to be removed.

Last, but not least, areas with strong wind shear and turbulence could be avoided, as well as areas where for example volcanic activities have ejected large amounts of dust into the

upper troposphere. This in turn would ensure maximum passenger safety and comfort.

Another area of interest in which real-time WVWV could be utilised is the prediction of the 'wet delay'. The combination of the WVWV information with atmospheric-humidity measurements can be used to estimate the impact of atmospheric moisture on radio-signal propagation. This could have important benefits for telecommunication.

The ability of the water-vapour channel to detect motion even in cloud-free areas can also be utilised in hurricane tracking and forecasting. The wind vectors derived in the cloud-free areas represent a mean flow in the middle atmosphere which is relevant when the movement of tropical storms is being tracked. Owing to the complexity of hurricanes, any additional information related to these severe weather phenomena is invaluable in reducing the damage they inflict.

The benefits of using the WVWV data in climate studies should not be underestimated. The complicated relationship between atmospheric humidity, wind fields and dynamics is of vital importance in improving our understanding of climate and climate change.

#### Conclusion

The automatic quality-control tools developed in support of the real-time Meteosat operations provide the potential for reduced human control for future operations, thereby leading to further cost savings. It has been demonstrated that it is possible to increase the frequency and quality of the Meteosat-derived products without calling for a satellite redesign. The important lesson to be learned here is that, as long as the intelligence of the system is vested in the ground segment, rather than on-board the satellite, improvements can be made at minimum cost by upgrading to the latest state-of-the-art equipment.

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