EUI, THE ULTRAVIOLET IMAGING TELESCOPES OF SOLAR ORBITER

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ABSTRACT

The scientific objectives of Solar Orbiter rely ubiquitously on EUI, its suite of solar atmosphere imaging telescopes. In the configuration discussed here, EUI includes three co-aligned High Resolution Imagers (HRI) and one Full Sun Imager (FSI). FSI and two HRIs observe in extreme ultraviolet passbands, dominated by coronal emission. Another HRI is designed for the hydrogen Lyman α radiation in the far UV, imaging the Chromosphere and the lower Transition Region. The current EUI design and some of its development challenges are highlighted.

EUI profits from co-rotation phases, solar proximity and departure from the ecliptic. In synergy with the other S.O. payload, EUI probes the dynamics of the solar atmosphere, provides context data for all investigations and helps to link in-situ and remote-sensing observations. In short, it serves all four top-level goals of the mission. For these reasons, the EUI suite is keenly anticipated in the European scientific community and beyond.

1. INTRODUCTION

The instrument and the scientific rationale summarized in this paper have been studied by scientists and engineers from the Royal Observatory of Belgium, the Centre Spatial de Liège, the Institut d'Astrophysique Spatiale, the Max Planck Institute for Solar System Research and the Mullard Space Science Laboratory. The presented version reflects an understanding of the payload definition and science goals that match the early 2006 mission status [1,2], prior to the probable merging of the ESA Solar Orbiter (S.O.) and NASA Sentinels [3] into one coordinated mission. The latter possibility was announced and proposed to the community at the October 2006 S.O. workshop, to which Proceedings the present paper belongs. As a consequence, some information provided below may soon change in priority or relevance.

Yet, the presented design offers dependable solutions, which assimilate the trade-offs between availability of resources and technical challenges of the reference S.O. mission on one hand, and achieving performance goals such as high spatial resolution and high image cadence on the other. Further, large parts of the scientific and technical analysis are expected to remain valid, such as certain conformity to a keep-it-simple philosophy.

The instrumental configuration is described in the next section. Section 3 details the science that can be addressed with this UV telescope suite and the S.O. payload as a whole. Section 4 highlights some of the foreseen challenges that the EUI development will face. Conclusions can be found in Section 5.

2. INSTRUMENTAL CONFIGURATION

In the configuration discussed here, EUI includes three co-aligned High Resolution Imagers (HRI) and one Full Sun Imager (FSI). FSI and two HRIs observe in extreme UV passbands, dominated by coronal emission. Another HRI is designed to select the H I Lyman α radiation in the far UV, imaging the Chromosphere and the lower Transition Region (TR) [4]. Table 1 specifies the intended temporal and spatial resolutions, field-of-view (FOV) as well as passbands.

Table 1. Main characteristics of the EUI channels

EUI	Field of View (arc min)	Spatial resolution (2 pixels)	Bandpass centre (nm)	Cadence, exp. time ranges (s)
HRI 174	16.6	1 arc sec	17.4	1-60
HRI hot	16.6	1 arc sec	13.3 or 33.5	1-200
HRI Ly α	16.6	1 arc sec	121.6	1-10
FSI	5.4 deg	9.5 arc sec	17.4	30-3600

The HRIs are off-axis Gregorian telescopes (two mirrors) with a 30 mm pupil diameter, while the optical design of the FSI is based upon a single off-axis mirror with a 5-mm pupil diameter. The baseline formats of the cameras are 2k x 2k for the HRI, and 4k x 4k for the FSI.

As a result of ESA directives, and except for the pupil aperture size, this embodiment of the EUI exhibits no

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divergence with respect to the Payload Definition Document [2]. The FSI FOV amounts to 5.4°, i.e. 4 solar radii at perihelion (0.22 AU) while the HRI pixel corresponds to 80 km at disc centre. The 4k x 4k FSI detector format is worth a comment. Despite the technological challenge that it might represent, it is considered essential in order to bridge the global view uniquely offered by the FSI with the high-resolution payload, including the HRIs. One FSI pixel corresponds here to 90 HRI pixels or 22 EUS pixels, instead of 4 times these values with a 2k x 2k detector. The values promised by the 4k x 4k format are acceptable although one could hope for an even more gradual transition. Anyhow, the FSI optical design was shown to authorize this solution [5] and the corresponding telemetry increase can be handled by simple rebinning outside the region of interest or by more advanced lossy compression schemes [6]. Independently, the FSI telemetry allocation is felt as being underestimated.

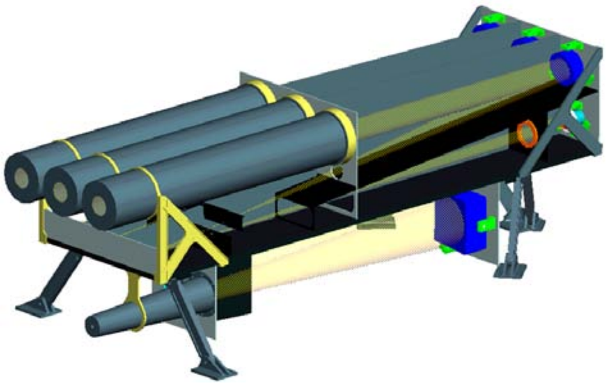

Figure 1. A possible configuration of the EUI suite

As to the foreseen cadence, it has been an HRI design goal to make it in agreement to its spatial resolution. As shown in [7], time aliasing (whether undersampling or kinetic blurring) is to be avoided as much as possible. This is further discussed in the next section but it affects also the entrance aperture (Section 4.1.), the camera electronics and all design elements in general. Likewise, FSI could be envisaged to run (sometimes) closer to its 30 s ideal cadence. Other challenging areas of the EUI design are pointed out in section 4.

3. SCIENCE RATIONALE

3.1. Bandpasses

EUI is a fundamental component of the Solar Orbiter scientific payload. FSI will provide information on the global structure and changes of the solar atmosphere and describe the boundary conditions of the near-Sun heliosphere; it will reveal the evolution of regions responsible for Solar Energetic Particles (SEPs) and of those corresponding to the source of the fast or slow solar winds. During certain epochs, FSI will observe the "far-side" or the poles. Coronal observations by FSI will definitely help in supplying data to link the surface with the inner heliosphere [1]. The primary option considered is a bandpass centred at 17.4 nm, displaying the Active Regions (AR), Quiet Sun (QS), Coronal Holes (CH), prominences, flares and other coronal events of interest. Additional observations of chromospheric material would however provide complementary information.

To understand the physics that drives large-scale or even global changes in the solar atmosphere, it is essential to investigate the processes acting at hitherto-unexplored small scales, from the Chromosphere to the Corona. This is the purpose of the HRIs. They will provide high-resolution (80 km pixel size for a 0.22 AU perihelion) images of the solar atmosphere in the chromospheric and low Transition Region (TR), the cool (~1 MK) Corona and the hot (>2.5 MK) Corona.

The Lyman α HRI channel at 121.6 nm will deliver information on the physical processes at work in the upper Chromosphere and low TR [4]. It has been chosen instead of a bandpass centred at He II 30.4 nm because it allows a cadence higher by circa 2 orders of magnitude while ensuring high spectral purity [8]. In the region of the atmosphere where Lyman α is emitted, the photospheric magnetic field expansion has already occurred. It is thus important for studies of the coupling of the Corona with the Chromosphere (EUS) [9,10] or the photosphere (VIM). H I Lyman α emission is also seen in the off-limb Corona, thus providing the "bottom" information needed to interpret Lyman α coronagraph measurements (COR).

The 17.4 nm HRI channel will show the plasma from the upper TR (Fe IX line, peak formation temperature around 0.8 MK) and Corona (Fe X line, peak formation temperature around 1 MK). Its merit has been extensively demonstrated by SOHO-EIT, TRACE and CORONAS-SPIRIT. It is again foreseen by STEREO-SECCHI, SDO-AIA and PROBA2-SWAP.

Concerning the hot coronal HRI channel, a choice exists from the 13.3 nm (Fe XXIII line, peak formation temperature 14 MK) to the 33.5 nm (Fe XVI line, peak formation temperature 2.6 MK) bandpass. The scientific incentive for this channel is to ensure the temperature coverage of the hot Corona in active regions and to observe theoretically predicted high temperature signatures of small-scale coronal heating events. The 33.5 nm bandpass is the current baseline, but the final decision will be taken on basis of further scientific and technical considerations.

Only with a set of 4 telescopes can EUI fulfil all the requirements for EUV imaging specified in [1]. The 5 science goals developed below emphasise three mission characteristics of Solar Orbiter, namely close-up, out-of-ecliptic and nearly co-rotating view points.

3.2 Coronal heating and small-scale structuring

Numerous mechanisms have been proposed to solve the long-standing problem of coronal heating; see e.g. [11,12] for reviews. Various physical mechanisms, from MHD to kinetic ones, have been invoked. The choice of the mechanisms that are operating in the solar TR and Corona depends strongly on the spatio-temporal structure of the plasma in the solar atmosphere. Dominant space- and time- scales of energy storage and dissipation still remain elusive [13,14,15,16].

Modern observations (e.g. YOHKOH, SOHO, TRACE) demonstrate that the solar TR and Corona are highly structured and dynamic to the limit of the instruments' spatio-temporal resolution (e.g. [17,18]). This indicates that structures at even finer scales can be found. HRI spatial resolution will be 160 km at perihelion, around 5 times better than the best resolution available today (by TRACE). Determination of smaller spatial scales in the TR and Corona will provide new constraints to coronal heating models. High-resolution observations will allow observing important physical processes such as magnetic reconnection and MHD waves.

The relative importance of reconnection (nanoflare theory, [19]) and waves for coronal heating is still unclear. Observations by HRI, using its high spatial and temporal resolutions, may be used to perform statistical studies of nano- and possibly picoflare energy distribution and thus greatly advance our understanding of this heating mechanism (e.g. [20]). Complementary observations by EUS will provide the information on the radiance of structures in spectrally resolved lines and Doppler velocities, thus constraining the thermal properties of plasma and its dynamics.

A novel approach suggested by recent numerical simulations [21,12] indicates that new signatures of the nanoflare heating can be detected at high temperatures (above 2 MK). A support for this theory is provided by soft X-ray observations of microflares at high temperatures (e.g. [22]). To investigate this hypothesis in detail, a hot coronal channel needs to be implemented. The combination of the hot HRI channel with the EUS spectra will be essential for the investigation of plasma dynamics at high temperatures [23,10].

Due to the high spatio-temporal resolution made available, HRI, EUS and VIM will offer new information on the origin and evolution of ephemeral regions, blinkers, spicules, explosive events, etc. It could eventually become possible to distinguish between activity arising spontaneously in the corona using its stored magnetic energy and the phenomena that need additional drivers from below. EUI will serve as an important tool for detecting coronal MHD waves and oscillations, and for measuring their properties. Waves and oscillations detected in loops [24,25] and plumes [26] may serve to determine the magnetic field and plasma parameters in the solar Corona. They are the subject of the expanding discipline of coronal seismology. All science goals of this sub-section would require a cadence homogeneous to the pixel size, that is better than 1 s, or the highest possible.

3.3. Eruptive phenomena

Powerful energy release processes like flares and coronal mass ejections (CMEs) will be observed by EUI as well. Tracking of active regions will permit to observe flaring of various magnitudes. The structure of the flare core will be well visible by HRI in both coronal channels. The flare ribbons will be examined in Lyman α with unprecedented cadence and spectral purity. Together with STIX observations, high spatial and temporal resolution images of the HRI, especially in the hot coronal channel, will help in determining the dominant scales of energy release during the flaring process (e.g. [27, 28]).

Large flares are often accompanied by SEPs that will be detected by EPD (e.g. [29]). Observing the particle acceleration sites with STIX and HRI could be an ambition of the mission, even more now that S.O. is to be combined with the NASA Sentinels programme. However, maximizing the chance of having them in the FOV of the high-resolution payload including the HRIs would need to be carefully prepared (cf. section 4 and [30]). Additionally, during the observations of the "far side" of the Sun (as seen from the Earth), FSI will image the sources of backside particle events, acting thus as a far-side sentinel [3].

CMEs will be primarily identified by COR, but the CME onsets (if on the visible side or at the limb) can be well detected by FSI using observations of filament or prominence eruptions, coronal dimmings, EIT waves and post-eruption arcades [31]. EIT-like cadence (12 minutes) or better is needed for this purpose. When pointed to a CME source region, all three HRI channels will be useful to observe CME-associated phenomena at high spatial and temporal resolution.

Due to the Solar Orbiter proximity to the Sun, the association of CMEs with their interplanetary counterparts (ICMEs) detected by MAG and SWA will be easier to establish than with ICMEs detected at 1 AU (e.g. [32,33,34]). Therefore, the properties of ICMEs detected *in situ* and their source regions observed by EUI and VIM (and possibly EUS) can be more readily compared. During the observations from a nearly co-rotating vantage point, the VIM data combined with the HRI images of the Corona will allow tracking the evolution of the magnetic helicity content (e.g. [35]) for longer periods than is currently possible from near-Earth observations. The amount of helicity carried away from the Sun by CMEs can be compared with the helicity content in the corresponding interplanetary magnetic clouds [36]. The CME-driven shocks may be detected as type II radio bursts by RPW, and EUI observations can be used to address such topics as relative starting times, location and nature of the radio sources.

3.4. Origin of the fast solar wind

Coronal Holes (CH) are viewed as the source of the fast solar wind. The most prominent features within polar CH are plumes, ray-like structures which extend over several solar radii. Plumes are cooler and denser than their surrounding [37,38,39]. Whether the fast solar wind originates from plumes or inter-plume regions is still a matter of debate [40,41,42]

Some of the problems in resolving this issue are caused by the low contrast between the emission of plumes and their environment. This is worsened by the location of all present day remote sensing platforms near the ecliptic plane, creating ambiguities due to the integration along the line of sight. The out-of-ecliptic and the close-up view points will mostly resolve those problems and allow the study of plumes in detail.

In order to carry out these tasks, the HRI channel at 17.4 nm will provide the needed high-resolution images to look at the possible fine structure of plumes. The Lyman α channel will be used to study the morphology and dynamics of plume footpoints in relation with the structure and evolution of the photospheric magnetic field provided by VIM.

It is also essential to establish whether there is a link between the plumes observed in the Corona and the density structures observed *in situ* in the fast solar wind [43,44]. It is expected that at distances of about 45 solar radii the fast solar wind will not be as uniform as observed by Ulysses at greater distances. The observations of equatorial CH, during the first phase of the mission, and polar CH, during the later out-of-ecliptic phase, will allow us to investigate the acceleration of the fast wind and its propagation into the heliosphere. Solar Orbiter will provide the means to solve this problem during the quasi co-rotation phase when it can observe the same fast solar wind stream for an extended period of time. The FSI images will be combined with the COR white light images of the inner Corona (using the overlap of the two fields of view from 1.2 to 2 solar radii) to map and follow the evolution of coronal holes and their fine structure.

The solar wind fluctuations observed *in situ* have characteristics of magneto-hydrodynamic turbulence. A major challenge is to understand the origin of such turbulence in the solar wind and identify the links between activity on the Sun's surface and the subsequent evolution of the inner heliosphere. The presence of Alfvén waves is a main characteristic of the fast solar wind at radial distances below 1 AU [45]. They seem to be of solar origin, even if such a picture has not been completely confirmed. To validate such a hypothesis the close-up view point, the co-rotation and out-of-ecliptic characteristics of Solar Orbiter are essential. EUI high resolution coronal images at different temperatures will allow measuring the coronal activity above the polar regions of the Sun. Such an investigation will be complemented by the study of multi-temperature plasma flows performed by EUS. FSI will help to identify the link between such activity and the large-scale configuration of the Corona provided by COR. It is also important to know the 3-D local plasma and magnetic field conditions, which will be identified using the *in situ* measurements by MAG and SWA.

3.5. The formation of the slow solar wind

There is a debate about the source of the fluctuating slow solar wind. Does it originate at the edge of streamers (e.g. [46]), from loop destabilisation inside streamers (e.g. [47]) and/or from the boundary of coronal holes [48,49]? This latter region is expected to be a location of continued magnetic field disruption since coronal holes rotate quasi-rigidly compared to the differentially rotating photosphere. Considering the timing of the mission we can expect to make such an investigation both on equatorial (during the first phase of the mission) and polar CH (later phase). The close-up view point will reduce the ambiguities in identifying the small-scale regions where the destabilization of the boundary occurs (local reconnection).

The large field of view of the FSI coronal images provides information on the global scale. These will be completed by corresponding high-resolution images at similar temperature, provided by the HRI channel at 17.4 nm. With the enhanced resolution of the FSI (4.75 arc sec) we may observe the same structure with the two instruments. The different source regions are likely to have different compositions in the corresponding outflow. This issue will be investigated together by EUI and EUS.

Linking coronal observations with the properties observed in the heliosphere using *in situ* data (e.g. from SWA) will be possible. The charge states of the solar wind ions represent a clear imprint of the conditions reigning in the source region of the solar wind (up to a few solar radii).

3.6. The third dimension of the solar Corona

Although NASA's STEREO mission will specifically address the three-dimensional structure of the solar Corona, both STEREO spacecraft will be situated very close to the ecliptic plane. In some cases this gives an uncertainty to the 3-D reconstruction that will be performed by STEREO. The out-of-ecliptic locations of the Solar Orbiter will provide a unique vantage point for the observations of the Sun and its atmosphere. Together with the COR instrument, FSI will provide important information on the large-scale structure and phenomena of the solar Corona, including polar coronal hole boundaries, streamers and CMEs. The extrapolations of the photospheric magnetic field (measured by VIM) into the Corona and further into the heliosphere can be compared with large-scale structures observed through remote sensing by FSI and COR, and *in situ* by SWA and MAG. Although it is generally well established that streamers are associated with the coronal neutral sheet (observed *in situ* as the heliospheric current sheet) the longitudinal distribution of plasma in the streamer belt is still unknown [50]. FSI will provide us with the observations of coronal structures underlying streamers (e.g. [51]). A special topic of research concerns active region streamers, i.e. those not directly associated to the heliospheric current sheet [52]. Additionally, thanks to the large field of view of the FSI allowing overlap with the COR field of view, direct comparison of structures observed in the EUV and in the white light becomes possible. *In situ* instruments -in particular MAG and SWA- will allow us establishing the link between the streamer structure observed by FSI and COR with the structure and evolution of the heliospheric current sheet (e.g. [53]).

4. CHALLENGES

Solar Orbiter is known to raise a number of technical issues, including to its payload [54,55]. We do not discuss here the thermal management that must be established to ensure the safety of the instrument and its continued performance. A novel approach to cope with the thermal load in normal incidence telescopes operating above 50 nm is described by [56]. Thermal matters come on top of the traditional aspects that affect EUV imaging telescopes: protection against contamination [57], ground- and space-based calibrations, mechanism reliability, baffling, alignments, etc. This will happen in a context where resources are sparse: mass, power and volume are restricted, while large baffles would be required to dilute the thermal load for example. In this section, we discuss two topics that are less often underlined, namely the availability of sufficient signal for given spatial and temporal resolutions and operational, telemetry, and software strategies. Needs for technological developments of EUI optical elements are finally mentioned.

4.1. Radiometric considerations

Best estimates of the expected signal for all four baselined channels and for various solar regions are reported in Table 2 for FSI and in Table 3 for HRI.

Owing to its low (9.5") required angular resolution (still yielding a spatial resolution of about 1500 km at 0.22 AU) and to its high throughput, FSI enjoys a signal larger than 1000 detected ph.px^{-1}.s^{-1} in Active Regions despite its small (5 mm) pupil diameter. Assuming Poisson noise dominance, FSI could run at 10 Hz while maintaining an SNR of 10 (in ARs). In contrast, and except for Lyman α observations [8], the high resolution payload is photon starving [7]. This is one of the main drivers in selecting coronal HRI bandpasses and the reason for their larger pupil diameter (30 mm minimum). The selected options offer nevertheless an SNR of at least 10 for a 4 s cadence (assuming uniform radiance within pixels and shot noise dominance). This will actually be a great breakthrough as such. Of course, the effective areas must still be improved as much as

Table 2. Radiometric assessment for FSI, 5 mm pupil diameter, 9.5 arcsec/pxl (2x2 rebinned), 1440 km/pxl at 0.22 AU

Passband	Coronal Hole		Quiet Sun		Active Region		Flare (M2 Class)	
	ph pix^{-1} s^{-1}	Spectral purity	ph pix^{-1} s^{-1}	Spectral purity	ph pix^{-1} s^{-1}	Spectral purity	ph pix^{-1} s^{-1}	Spectral purity
Fe IX-X 17.4 nm	21	76%	108	81%	1121	84%	8.6x104	17%(Fe IX-XI) 35% (continuum)

Table 3. Radiometric assessment for HRI, 30 mm entrance pupil diameter, 0.5 Arcsec/pxl, 80 km/pxl at 0.22 AU

Passband	Coronal Hole		Quiet Sun		Active Region		M2 Flare except Ly α	
	ph pix^{-1} s^{-1}	Spectral purity	ph pix^{-1} s^{-1}	Spectral purity	ph pix^{-1} s^{-1}	Spectral purity	ph pix^{-1} s^{-1}	Spectral purity
Fe IX – X 17.4 nm	1.6	84%	7.1	87%	68	92%	3563	30% (Fe IX-XI) 44 %(continuum)
H I Ly α 121.6 nm	292	95%	460	97%	1350	92%	3-15×104 (X class)	---
Fe XIX-XXIII 13.3 nm	0	---	0.1	---	1.3	27%	8.2×104	98%
Fe XVI 33.5 nm	0.1	---	0.86	26%	27	65%	4142	72% 14 % (cont.)

possible via optical elements progresses and instrumental design. We can also hope that the filling factor of some solar features will be low, enhancing the contrast of the scenes and the brightness of these objects. Finally, HRI observations of small flares will not encounter any shortage of photons. It is therefore meaningful to make the cameras able to run at a cadence of few Hz [7].

4.2. Operations, telemetry and onboard software

Another critical bottleneck of the EUI scientific aptitude resides in its telemetry (20 kbps), the suite being indeed capable of producing data in excess of the allocated rate by 2 to 3 orders of magnitude. Maximizing the EUI science requires balanced strategies for target selection, *a posteriori* image filtering and data compression. Reference [6] demonstrates compression of solar EUV images up to a factor 50 with only 0.01% of the pixels deviating more than the expected Poisson noise. Further progress of the compression ratio is being investigated. Yet, image compression alone cannot solve the telemetry shortage and onboard filtering of data based on predetermined science priorities and payload coordination is anticipated.

The EUI instrument suite does not have a pointing system for target selection but relies instead on the spacecraft pointing and tracking as a whole. Given the limited telemetry allocation, adequate target selection could be key in optimising the science output of EUI and the S.O. mission as a whole. Observation plans are intended to be uploaded a few weeks before the start of the perihelion passages. However, most solar phenomena are sporadic and not predictable so that the most interesting events will likely be missed by predetermined plans. An autonomous payload mode could remedy this by determining on board the optimal pointing. While simple 'centre of disk' or pre-selected spacecraft pointing is undoubtedly the safest strategy for the first perihelion passage, it would be more rewarding to have target selection sometimes activated during later phases of the mission. Simple and robust algorithms can achieve this within the overall frame of preset operation programs. Such targets could include developing loop systems, newly emerged active regions, post-eruptive activity, dynamic filaments and Bright Points. These algorithms will be applied to FSI data and will output a preferred pointing target to the platform that can accept - or not- to switch the S/C and its payload into one among few preset modes. Such an approach is studied by NASA [58] and also implemented by ESA for the PROBA2 satellite [59]. In combination with onboard notifications for *in situ* transient features, these algorithms can help to better link remote-sensing and *in situ* data.

4.3. Technological development of optical elements

Technological projects are ongoing to improve and/or assess the various critical elements of the EUI design. The development and testing of improved multilayers and metallic or interference filters is essential to the ultimate performance of the instrument as well as to its robustness against thermal stresses, ionizing particles, irradiation, dust or ageing. As to the focal plane imaging detectors, a number of options must be evaluated and compared. A project aiming at imaging devices based on wide bandgap semiconductors [60] is funded since the summer 2006; backthinned APS and CCD are also among the options for the EUV channels, while intensified APS are the baseline for the HRI Ly α channel. More resources need to be devoted to the full assessment of the candidate technological solutions.

5. CONCLUSION

The EUI instrumental design and its science rationale have been presented. They illustrate the capabilities and the goals of a “general purpose” EUI suite, compliant with [1] and [2]. With the probable enhanced coordination between Solar Orbiter and the Sentinels, some parts of this paper may turn obsolete but others may gain importance. The interested reader is therefore invited to collect updated information at http://eui.sidc.be or to communicate directly with the authors.

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