HIGH RESOLUTION MAPPING WITH SMALL SATELLITES

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ABSTRACT:

Civil space-borne Earth surface mapping started in 1972 with a 80 m GSD provided by ERTS, later renamed to Landsat-1. Nowadays, the GSD approaches 1 m or even less. This trend was supported by the improvements in divers fields of technology as for instance optics, mechanics and materials, electronics, signal Optical Information Systems processing, communications and navigation. The space-borne mapping systems always attempted to achieve the highest ground resolution possible with the available technology at the given time. Also mass, volume and power consumption of the spacecrafts and instruments followed the trend to miniaturization. SAR systems are an alternative to passive optical systems; they also benefit from the technology improvements. But the most promising prospects for high resolution mapping with small satellites are connected with passive optical systems, especially push-broom systems. The paper tries to analyse how far can we go in decreasing the GSD using instruments and spacecrafts decreasing in size, mass, and power consumption. In this context the paper deals with important parameters for mapping with small satellites as spatial resolution, radiometry, mass, volume, power consumption, microelectronics, pointing accuracy and stability, data volume and transmission. From the viewpoint of technology, space-borne mapping systems using small satellites are feasible. It is a question of market requirement and market behaviour whether or not these small satellite-based mapping systems can compete with the existing mapping systems, space-borne or airborne.

1. INTRODUCTİON

With the launch of SPUTNIK-1 on October 4, 1957 we experienced the beginning of the space age, but it took about 15 years to launch a satellite dedicated to civil space-borne Earth surface imaging: the ERTS (Earth Resources Technology Satellite) spacecraft, later renamed to Landsat-1. The MMS (Multispectral Scanner System) instrument provided a spatial resolution of 80 m and a swath width of 185 km. With Landsat-4 a more sophisticated multi-spectral imaging sensor was launched in 1982: TM (Thematic Mapper) with a spatial resolution of 30 m. Further important sensors for Earth surface imaging are for instance:

- MOMS-01 on Shuttle, 1983
- HRV (High Resolution Visible) on SPOT-1 – SPOT-4 satellite series of CNES (SPOT-1 was launched in 1986)
- MSU-E and MSU-SK on Resurs-01 satellite series of the former Soviet Union (Resurs-01-1 was launched in 1985)
- LISS cameras on IRS series of ISRO (IRS-1A was launched in 1988)
- OPS on JERS-1 of NASDA in 1982
- AVNIR on ADEOS of NASDA in 1996
- OSA on IKONOS-2 of Space Imaging in 1999
- PIC on EROS-A1 of Image Sat in 2000.

Of course, this list is incomplete. There are numerous sensors of different types (mechanical scanners, push-broom scanners, matrix systems) from many countries, like for instance Brazil, China, Argentina, Korea, UK, Germany [1].

The CCD line detector technology was introduced with MSU-E (Multispectral Scanning Unit-Electronic). It was first flown on Meteor-Priroda-5 in 1980 and provided a spatial resolution of 28 m and a swath width of 28 km. Table 1 shows the major Earth surface imagers and figure 2 the trend of resolution improvement (decrease of GSD) over the time. The number of space-borne mapping systems indicates the need of high resolution maps using the best available technologies. The background information for these needs is given in [2].

The space-borne stereoscopic along-track imaging was introduced by MOMS-02. This three-line camera system was flown on Shuttle STS 55 (April/May 1993) and MIR/Priroda (launch April 1996). Also WAOSS-B on BIRD (launch October 2001) uses the three-line principle, but exploiting 3 CCD lines on a single focal plane behind a single optics (it is a modified version of WAOSS flown on the Russian mission Mars-96, launched in November 1996 but failed to obtain the Mars orbit). Early Bird and IKONOS-2 provide stereo capabilities using the along-track slewing feature.

Beside the passive optical systems, there exist also active systems able to generate DTMs (Digital Terrain Models) based on the SAR (Synthetic Aperture RADAR) or RADAR Altimeter principles. Due to the immense improvements in such divers fields as optics, mechanics and materials, electronics, pattern recognition, signal processing, computer technology, communications and navigation, all those systems are matured on a very sophisticated level. Nevertheless, the most promising prospects for topographic mapping with small satellites are connected with passive optical systems, especially push-broom systems. So this paper will concentrate on this kind of passive topographic mapping technology.

Figure 2 shows the decrease of GSD which took place since Landsat-1 in 1972. A similar trend can be observed in mass and power consumption decrease. Of course, the decrease is not that steep as in GSD because of the larger optics needed for smaller GSDs. The question is, how far can we go with decreasing

Mission	Launch date	Instrument	Best GSD	Swath width
Landsat-1	July 1972	MSS	80 m	185 km
Landsat-4	July 1982	TM	30 m	185 km
Resurs-O1-1	Nov 85	MSU-E	40 m	45 km
SPOT-1	February 1986	HRV	10 m	60 km
IRS-1A	March 1988	LISS-II	36 m	74 km
JERS-1	October 1993	OPS	20 m	75 km
IRS-1C	December 1995	PAN	6 m	70 km
ADEOS	Aug 96	AVNIR	8 m	80 km
EarlyBird	December 1997 (failed)	EBP	3 m	3 km
Landsat-7	Apr 99	ETM+	14 m	185 km
EO-1	Nov 00	ALI	10 m	185 km
IKONOS-2	Sep 99	OSA	1 m	11 km
SPOT-5	May 2002	HRS	2.5 m	60 km
Terra	December, 1999	ASTER	15 m	60 km
EROS-A1	December 2000	PIC	1.8 m	12.5 km
QuickBird-1	Nov 00	BGIS 2000	1	27 km

Table 1 Some civil Earth surface imagers

instrument size, mass, and power consumption, and decreasing the GSD at the same time. In other words, what are the prospects for topographic mapping using small satellites in the next decade.

2. TOPOGRAPHIC MAPPING CONCEPTS

There are several possibilities to perform topographic mapping, most of them can make use of line or matrix technologies.

1) Across-track stereo (see fig. 3) due to side viewing feature (e. g. SPOT-1 – SPOT-4)
2) Along-track stereo
2.1) 1 sensor concept using forward/backward slewing feature (see fig. 4)
   Phase 1 imaging in forward slewing mode
   Phase 2 imaging in backward slewing mode
   (e. g. IKONOS, EarlyBird (matrix camera), QuickBird)
2.2) 2 sensor concept using forward/backward looking sensors with
   - 2 cameras, e. g. HRS on SPOT-5
   - 2 line arrays of a single camera, e. g. OPS on JERS1, ASTER on Terra (see fig. 5)
2.3) 3 sensor concept using forward/nadir/backward sensors with
   - 3 cameras, e. g. MOMS-02 on STS-55 and MIR/Priroda
   - 3 line arrays of a single camera, e. g. WAOSS-B on BIRD (see fig.6).

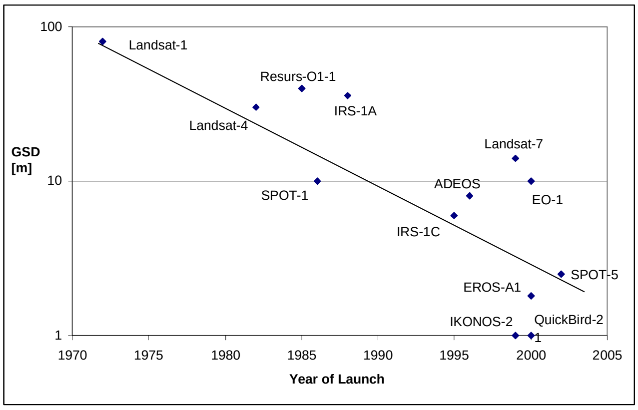

Figure 2 Some civil Earth surface imagers, trend of GSD

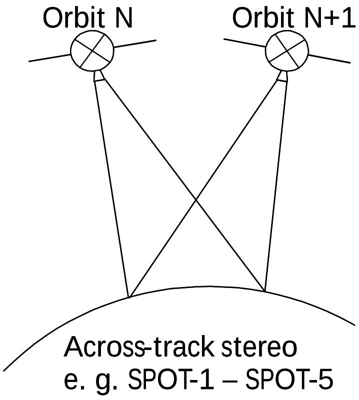

Figure 3 Across-track stereo principle

3. IMPORTANT PARAMETERS FOR MAPPING WITH SMALL SATELLITES

IMPORTANT PARAMETERS FOR MAPPING WITH
In this chapter only some major features are described and a few suggestions are given to support miniaturization in order to come in the range for small satellite designs.

3.1 Spatial resolution aspects

Some major features are considered which influence the image quality from the spatial resolution point of view. A very effective way to describe the image quality is to use the Modulation Transfer Function MTF. It can be cascaded in order to combine all the different influence elements

$$MTF_{SR} = MTF_{Optics} \cdot MTF_{LM} \cdot MTF_{J} \cdot MTF_{D} \qquad (1)$$

(SR – spatial resolution, LM – linear motion, J – jitter or random motion, D – detector)

MTF_{Optics} includes the diffraction part as well as the aberration part.

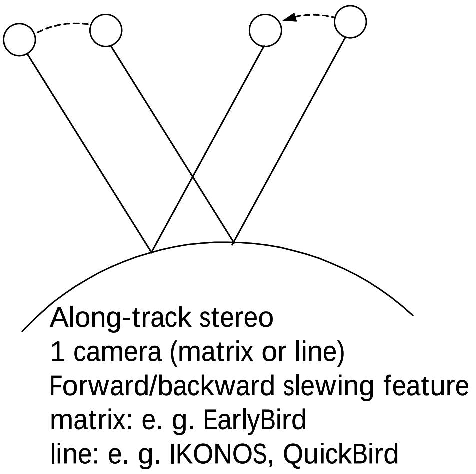

Figure 4 Along-track stereo using the slewing feature of the satellite or platform

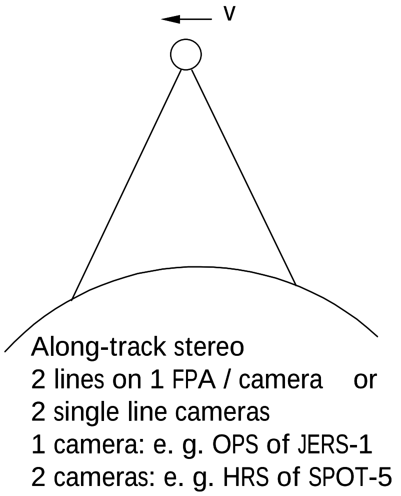

Figure 5 Along-track stereo with 2 sensors

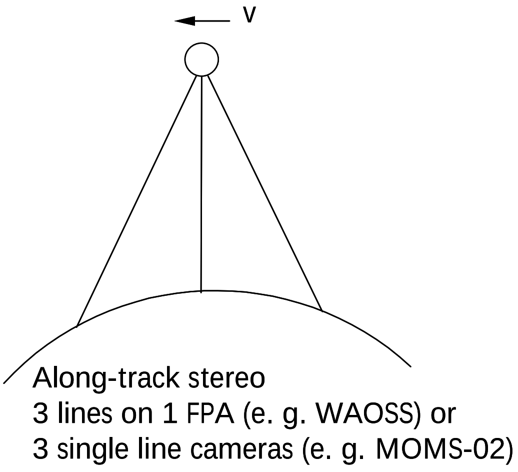

Figure 6 Along-track stereo with 3 sensors

For most of the operating systems, the optical system may be considered near diffraction limited and in focus. The Airy disk diameter d caused by diffraction is one of the important parameters which can be related to the detector pixel size x

$$d = 2.44 \cdot \lambda \cdot \frac{f}{D} = 2.44 \cdot \lambda \cdot F \tag{2}$$

with f the focal length, D the aperture of the optics, and λ the average wavelength of the radiation. If x is larger than d the system is detector limited, the resolution is determined by the detector. Otherwise the optics determines the spatial resolution. Figure 7 shows the borderline for an average wavelength of $\lambda = 0.55\mu m$ (green). The optics designs should be near to the borderline on the optics limited side in order to get maximum energy for the detector avoiding too large aliasing effects. F state-of-the-art CCD detectors with a pitch of 7 µm, a f/5.2 optics would satisfy this approach.
The MTF degradation due to linear motion of the satellite is

$$MTF_{LM}(f_x) = sinc(a_{LM} \cdot f_x) \tag{3}$$

where f_x is the spatial frequency, and a_{LM} the distance the target edge moves across the detector pixel. MTF_{LM} only effects the MTF in the direction of the motion. The distance a_{LM} is $v \cdot \Delta t$. In many cases Δt is close to the dwell time and MTF_{LM} is approximately MTF_D. As a rule-of-the-thumb, when the linear motion causes an image shift less than about 20 % of the detector size, the effect on system performance is minimal.

For MTF_J (jitter or random motion) is assumed that the jitter is a superposition of different high-frequency motions so that the central limit theorem can be applied. It says that many random movements can be described by a Gaussian distribution

$$MTF(f_J) = \exp(-2\pi^2 \sigma_J^2 f_J^2) \tag{4}$$

with σ_J the rms random displacement. As a rule-of-the-thumb, when σ_J is less than about 10 % of the detector size x, system performance is only minimal effected. Attitude control systems for pointing accuracies and stabilization to support high resolution functions on micro satellites are under development. In some cases, disturbing vibrations may also be avoided by simply switching off the active control functions during the relatively short imaging phase.

3.2 Radiometric aspects

The number of photoelectrons generated in a solid state camera is

$$n_{pc} = \frac{A_D \cdot \mathrm{T}_{Optics} \cdot t_{\mathrm{int}}}{4F^2} \int_{\lambda_1}^{\lambda_2} R_d(\lambda) L(\lambda) d\lambda \tag{5}$$

(A_D – detector area, T_{Optics} – transmission of the optics, t_{int} – integration time, F –f-number, R_d – detector responsivity, L – radiation flux) with $t_{int} < t_{dwell}$.

Once the detector is selected, A_D and R_d are given. L is also given as well as F and T_{Optics} when the optics is selected or designed taking into account the technological or mission constraints. $\Delta\lambda$ is fixed in most cases, so that the only real variable part is the integration time t_{int}. For a satellite in LEO, the satellite ground track velocity is about 7 km/s. In other words, the dwell time is 1 ms for a ground sample distance GSD of 7 m. For high resolution imagers with GSD of about 1 m, t_{int} < 1/7 ms is too short for a sufficient good signal and SNR.

$$t_{dwell}(1m)/t_{dwell}(10m) = 1/10 \qquad (6)$$

Even more severe is the influence of the pixel field of view (IFOV).

$$IFOV(1m)/IFOV(10m) = 1/100 \qquad (7)$$

Taking both aspects into account, redusing the GSD by a factor of 10^{-1} causes a time related and geometry related decrease of energy at the detector of about 10^{-3}.

There are two possibilities to overcome this obstacle:

- use TDI technology with N stages in order to increase the signal N-fold and improve the SNR by the factor of $\sqrt{N}$ (this technology is used e. g. in the IKONOS and QuickBird missions)
- use the so-called slow-down mode in order to decrease the ground track velocity of the line projection on the surface.

with respect to the satellite velocity in order to obtain the necessary dwell time t_{dwell}.

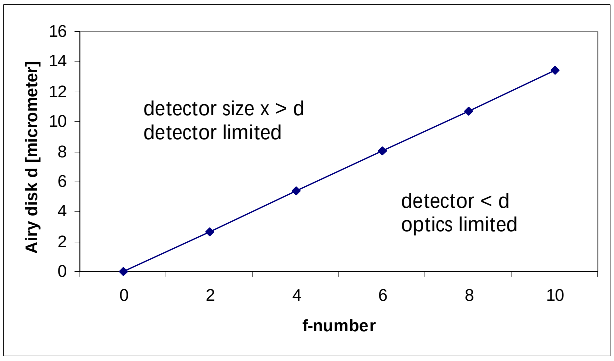

Figure 7 Airy disk parameter d as a function of the f-number F (λ=0.55 µm)

3.3 Mass, Volume, Power Consumption

3.3.1 Microelectronics: Since the launch of Landsat-1 in 1972, the progress in microelctronics enabled more sophisticated instrument designs. The developments for the MESUR Network Mission may serve as an example, how much microelectronics technology may influence the overall mission design. The MESUR (Mars Environmental Survey) Network Mission concept consisted of up to 16 small spacecraft (that time planned to be launched in 2001). As often in extraterrestrial missions, there was a pressure to miniaturization by need. Reference mission was the MESUR Pathfinder Mission, one of the first missions under NASA's Discovery program of smaller, low-cost missions to be launched 1997.

In [3] the benefits have been assessed which may occur when the electronics technology used in the MESUR Pathfinder mission is replaced by advanced microelectronics technology. The MESUR Network study team found out that advanced microelectronics packaging technologies could be applied to the implementation of subsystem functions for

- the Attitude and Information Management System AIMS
- the Radio Frequency Subsystem RF
- the Power and Pyro Subsystem PP.

As a result, a factor of three or better reduction in mass, volume, and power consumption were projected relative to the MESUR Pathfinder baseline (see table 8).

The key to realize these reductions lies in the utilization of industry-based advanced microelectronics packaging technologies, including:

- multichip module (MCM) technology
- three-dimensional MCM stacking
- Die stacking for memory.

	Pathfinder	**Network**	**Net Reduction**	**Fractional Reduction**
Mass	47 kg	11 kg	36 kg	4.3 x
Volume	46 dm³	6.5 dm³	39.5 dm³	7.1 x
Power	74 W	26 W	49 W	2.9 x

Table 8 Projected total reduction in mass, volume, and power consumption for MESUR Network in comparison to MESUR Pathfinder

The leverage of these reductions to the spacecraft is obvious. The advanced microelectronics packaging technologies have been widely used for instance in a joint NASA/DLR study for the ROSETTA lander carrying among other cameras a stereo camera with 10 mm GSD [4] and in a joint DLR/NASA three-line stereo camera concept for planetary exploration [5]. The effects have been remarkable. The latter concept resulted for instance in very small stereo camera for a GSD of 20 m and a swath width of 250 km from an orbit altitude of 250 km, and with a weight of 2 kg and a power consumption of 12.5 Watts including a 1 Gbit mass memory.

3.3.2 Detector: *Pixel size influence* - For mapping purposes the pixel size of the detector is projected via the focal length to the ground pixel size to be obtained, the smaller the detector elements x the shorter the focal length f (see figure 9). As an example, the stat-of-the-art CCD pixel size of 7µm results in a focal length of f = 4.2 m. Of course with smaller detector sizes less energy is integrated. If the sensitivity of the pixel element is not sufficient to obtain the necessary SNR, TDI needs to be applied or a so called slow-down mode allows to enlarge the dwell time to the sufficient extent (should not be used in stereo imaging).

Impact of staggered configurations - Volumes and mass of an optics depends significantly on the focal length and the aperture, but also on the image field size determined by the detector extensions. Using staggered line arrays (see fig. 10), the following effects occur:

- detector line length is halved
- image field area is reduced to one quarter
- focal length is halved
- the optics need to be of high quality for twice as many line pairs per millimeter with respect to the line pairs per millimeter necessary for the pixel size.

Staggered CCD-line arrays are used for instance in the SPOT-mission cameras.

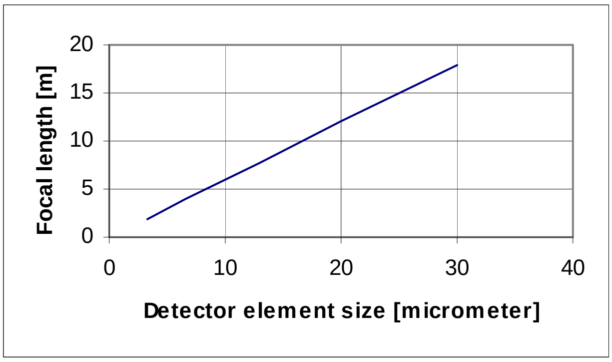

Figure 9 Dependence between detector element size x and necessary focal length f for a given ground pixel size of X = 1 m from an orbit altitude of 600 km

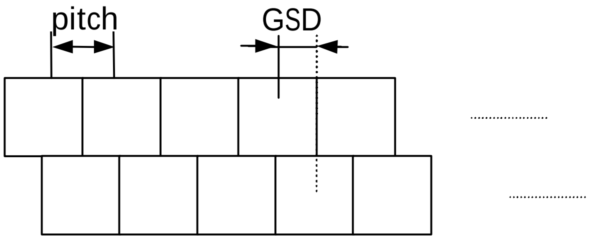

Figure 10 Staggered linear detector array configuration

3.3.3 Optics: The progress in production and test of optic systems enables now the utilization of highly efficient low-mass and low-volume optical telescopes for space applications. Examples are

- Use of aspheric lenses in refractive telescopes
- Use of folded arrangements for reflective telescopes (e. g. TMA)
- Use of sophisticated catadioptric telescopes.

Even if you can design a camera having weight compatible with a micro-satellite spacecraft, the volume of the lens system for high resolution space-borne imagers is a problem if you think of the restricted size envelope for piggy-back launch opportunities.

The Technical University of Berlin currently performed a study concerning an interesting optics construction approach: the Dobson Space Telescope, DST, [6]. The core element of DST is a 20 ´´ f/5 Newton telescope. The secondary mirror will be placed via four 2.1 m booms when the spacecraft is already in orbit. In order to fulfill micro satellite requirements it is folded to minimal space during the launch. This type of telescopes called truss design Dobson was originally invented by ambitious amateur astronomers. To increase the resolution for remote sensing purposes, a “Barlow lens” with a factor of 2.5 pushes the focal ratio up to f/12.5 which assures maximum possible magnification and a ground pixel size of about 1m from a 700 km orbit.

3.4 Pointing accuracy and stability

There are many activities going on to develop and test instruments, actuators, and algorithms to control the pointing with high accuracy. The obtained accuracies are between arcseconds and fractions of degrees. For mapping of the Earth’s surface, deviations from the necessary precisions can be corrected using precise ground control points. The pointing stability is of more importance in order to maintain the ground sample distance and the image quality. From an orbit altitude of 600 km, a GSD of 1 m equals an IFOV of 1.7 µrad or approximately 1/3 of an arcsec. During the dwell time, the drift shall be less than 20 % of the IFOV resulting in a drift rate of about 2.4 mrad/s or 8 arcmin/s in order to stay in the limit for minimal degradation of the MTF due to drift effects. When using the TDI principle to improve the SNR, for a 32 step TDI the tolerable drift rate becomes even 75µrad/s or about 15 arcsec/s!

3.5 Data volume and transmission

Data rate is a very important parameter for imagers on small satellites. Most small satellites use X-Band transmitters allowing about 100 MBit/s. The ground station contact time from LEO is about 10 minutes resulting in roughly 60 GBit to be transmitted. If no compression is applied, a quadratic image of 87 kByte x 87 kByte can be transmitted during the ground station contact time. Whatever is used, the store & dump mode or the real-time mode, careful planning of the orbit activities is of high importance to make most use of this bottleneck.

4. CURRENT AND PLANNED MISSIONS

This paper showed the problems connected with high resolution topographic imaging. But it showed also the possibilities resulting from the immense improvements in many fields of technology. So it is not surprising that there are a good number of small satellites (total mass < 500 kg) with high-resolution instruments (≤ 10 m GSD) in orbit or planned. Table 11 shows the missions which have no stereo capabilities.

The suite of small satellite mission in orbit or planned for topographic mapping is smaller (see table 12).

From the technology point of view small satellite missions for topographic mapping are feasible. Table 8 shows that even a GSD of 1 m is attacked. Once the performance concerning data quality for topographic mapping is proven, there is a chance to install mapping systems with a low cost space segment. When we restrict ourselves to civil applications, the market will show whether or not those systems can compete with SPOT-5 topographic maps (GSD of 5 m).

On the higher resolution side, those systems will compete with the standard aerial photography market. If for some reasons high-resolution maps with worldwide high repetition rates are required,the necessary coverage asks for many cost-effective systems. Then there is a high need to install more small satellites for topographic mapping.

Mission	**GSD [m]**	**Status**
Earth Observation-1/ NASA	10 m	launch November 2000
PROBA/ESA	5 m	launch October 2001
X-SAT/ Singapore	10 m	planned
EKOSAT-IR/ Germany, Israel, Korea	5 m	planned
MAC/ Korea, Malaysia	2.5 m	planned
DST/ Germany	1 m	planned

Table 11 Small satellite high resolution mapping missions, without stereo capabilities

Mission	**GSD [m]**	**status**
EROS-A1/ Israel	1.8 m	launch December 2000
Rapid Eye/ Germany	6.5 m	planned
Diamant-1/ Germany	5 m	planned
TOPSAT/ UK	2.5 m	planned
EROS-B/ Israel	0.82 m	planned

Table 12 Topographic mapping missions with small satellites

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