01 - PAST, CURRENT AND FUTURE SATELLITE MISSIONS AND THEIR APPLICATION TO IRISH HYDROLOGY

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Abstract
Remote sensing datasets have become increasingly useful in hydrology. Today, many satellite missions provide timely delivery of data with spatial coverage not achievable with terrestrial systems. The data provided can be useful in its own right or can complement ground sourced information. In this paper we will describe the past, current and planned satellite remote sensing platforms, which are most useful for hydrology globally and in particular for Ireland.

Although, at present, there are no exclusively dedicated hydrology satellite missions, remotely sensed data from other missions are and can be of great value to hydrology. For instance, meteorological missions such as CMORPH and the newly-launched Global Precipitation Measurement (GPM) initiative include coverage of Ireland. For evapotranspiration (ET) the MODIS ET global product gives estimates at 8-day, monthly and annual rates at the spatial resolution of 1km^2, and the GLEAM product and its daily estimates at 0.25^o.

In the past few decades, literature on the use of remote sensing to aid hydrology has vastly expanded with methods and data ranging from simple image interpretation for the extraction of water body extents to sophisticated processing of satellite altimetry data for used in data assimilation with hydro-meteorological forecasting and warning systems.

Satellites with active Synthetic Aperture Radar (SAR) and scatterometers and passive satellite platforms give estimates of soil moisture. SAR can provide fine spatial resolution coverage and can be scheduled for appropriate times. Scatterometers can provide near global coverage at spatial resolution of approximately 25km every few days, while passive methods such as AMSR-E on both ESA's SMOS and NASA's SMAP missions will provide estimates of soil moisture at the approximate spatial resolution of 10km every three days. Even the more distant, geostationary, meteorological satellites give estimates of soil moisture and the Gravity Recovery and Climate Experiment (GRACE) mission measures the water storage change with time.

Altimetry missions are extremely valuable in monitoring changes in water surface heights in both reservoirs, lakes and in rivers depending on their corresponding width. There are many such altimetry satellites, (e.g. ICESat GLAS, Envisat, Topex-Posidean, Jason and SIRAL) each with their own strengths and weaknesses. In this paper we discuss which of these missions are suitable for use in Irish hydrology applications

Satellite missions can be useful in monitoring water areas and in mapping the extent of flooding. Missions which use visible band sensors, such as Landsat, MODIS and SPOT have high spatial resolution, e.g. Landsat's and SPOT's spatial resolutions are 30m and 1.5 -6 m respectively; however, these can be affected by cloud cover and can only be acquired during daylight hours, while SAR can

penetrate clouds and be acquired throughout the day, but with coarser spatial resolution compared with visible band sensors. Visible band sensors, especially Landsat, can provide a unique dataset to study land-use change. The first Landsat satellite was launched in 1972 and there are now 43 years of 30 m resolution imagery for the globe.

Finally, we will discuss future planned satellite mission from both ESA and NASA and discuss if they will be useful to Irish hydrology. One of these missions is the planned NASA's Surface Water Over Topography (SWOT) mission. SWOT will have the capability to measure water levels every 50m with higher accuracy than previous altimetry mission and estimate discharge globally for rivers greater than 100m wide.

1. INTRODUCTION

For many regions of the world, the current hydrological and meteorological datasets derived from terrestrial in-situ measurements are not sufficient for adequate monitoring or modelling of the water cycle. Even in Ireland, this is the case to some degree. While Ireland has a large hydrologic collection programme, there are only 25 stations which can provide meteorological data at sub-daily intervals. This equates to approximately 1 station per 2800 km^2, while in the United Kingdom there is a meteorological station per maximum 500 km^2, and this is ignoring their large network of rainfall gauges.

It has been recognised for years that satellite remote sensing systems are valuable sources of complementary information for hydrology, despite there being no satellite missions dedicated exclusively to hydrology to date. Instead, remotely sensed datasets that are valuable for water resources purposes come from satellite missions from other fields, such as meteorology, oceanography and Earth surface mapping.

One of the main criticisms of using remote sensing datasets is the labour intensive task of processing the satellite data to make it useful. However, in recent time there has been a gradual move to releasing pre-processed datasets to the general scientific community, which can be used directly, without any user processing. One example of this is the European Space Agency's (ESA) river and lake database (available at http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/); however, it is currently only available for large rivers and lakes globally.

Most satellites operate over a wide range of the electromagnetic (EM) spectrum (ultraviolet to radar/microwave), with sensors detecting variations in energy in both the visible and non-visible area of the spectrum (Figure 1). However, some areas of the EM spectrums are completely absorbed by the atmosphere are not used in remote sensing, such as Gamma rays and X-rays. Some platforms, especially on meteorological satellites, directly measure how much of a specific area of the EM spectrum is absorbed. However, most remote sensing platforms are designed to collect reflected energy and are designed to operate in areas of the EM spectrums where little or no atmospheric absorption occurs. In general, as you move from shorter (gamma rays) to longer (Radar/Microwave, Radio) wavelengths, the absorption by the atmosphere becomes less.

There are two major orbits that nearly all satellites use called sun synchronous (or polar) orbits and geostationary orbits. Geostationary orbits seem stationary in the sky and take 24 hours to orbit the earth. To achieve this time of orbit, these satellites are approximately 36,000 km above the earth. Geostationary satellites are generally used for telecommunications and television broadcasting as well as for weather monitoring. Sun or polar synchronous orbits are generally used for environmental monitoring satellites. Their orbits are much lower than geostationary orbits, typically between 300 and 1,400 km above the earth and with an orbit time of ~ 90 minutes. As satellites pass the Polar Regions with an inclination angle near 90^o their orbits are called polar orbits. An inclination angle is the angle between the orbit and equatorial plane. Sun synchronous means that the area monitored is always radiated by the sun.

This paper is divided into three sections. In the first section we discuss how satellite missions can add to our current knowledge of the hydrological cycle, with particular emphasis on precipitation, evapotranspiration, soil moisture and water storage changes. The second section examines how satellite missions are useful for monitoring. That section will focus on estimating water surface heights and extents, identifying land-use change and water quality. The final section will discuss planned future satellite missions and their potential contribution to hydrology.

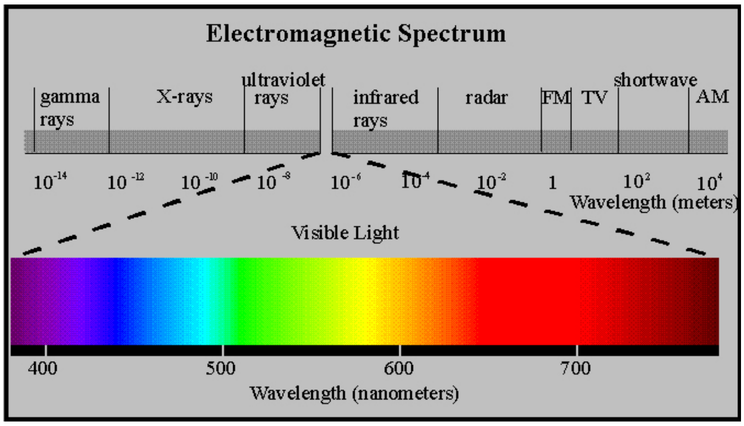

Figure 1: Electromagnetic (EM) Spectrum

2. SATELLITE MISSIONS AND THE HYDROLOGICAL CYCLE

2.1 Precipitation

In many areas of the world, the lack of an extensive and accurate raingauge network is one of the major challenges facing hydrologists. Even in countries with extensive raingauge networks, these networks may often not have the temporal or spatial resolution needed for many hydrological studies. This is the case in Ireland, where an extensive network of daily accumulation raingauge exists; however, there are only 25 sub-daily Met Éireann raingauges across the entire country. Precipitation from satellites may be useful in overcoming any shortcoming in the spatial or temporal of the in-situ network.

In many countries around the world, including Ireland, the use of satellite precipitation is becoming more widespread to overcome existing limitations in existing raingauge networks (Awange et al., 2015; Dinku et al., 2007, and Sampson et al. 2014). Awange et al. (2015) investigated the uncertainties in the various satellite precipitation products over the entire African continent. Dinku et al. (2007) validated multiple satellite precipitation products over East Africa and found that the performance of products varied greatly; however, some displayed good agreement with gauge area averages. Sampson et al. (2014) used precipitation from The Climate Prediction Centre morphing method (CMORPH) in looking at the impact of precipitation uncertainties on insurance loss estimates in Ireland's Dodder catchment.

Table 1 shows the four most widely used sources of satellite derived precipitation. Only two of these, CMORPH and the Global Precipitation Mission (GPM) cover Ireland. This is mainly because, to-date, most missions have mainly focused on the tropical zones of the world. CMORPH (Joyce et al., 2004) is a high spatial (8 km at equator) and temporal (30 minutes) resolution gridded product that combines precipitation estimates from a low orbit microwave satellite (such as TRMM) with information from geostationary satellites' (e.g. Meteosat and Global Telecommunications System stations) infrared data. The GPM is a major advance in the remote sensing of rainfall. GPM is centred on the development of a Core Satellite, which is serves as the calibration reference system to enable the integration of additional satellites (Smith et al., 2007).

Table 1: Characteristics of the most popular satellite precipitation products

Mission	Resolution	Latitude Extent	Temporal Scale	Time Period	Reference
Tropical Rainfall Measuring Mission	0.25°	50 N - 50 S	3 hours	Nov 1997 - Jul 2014	Simpson et al. (1988)
NOAA CMORPH	0.0728°	60 N - 60 S	30 minutes	Dec 2002 - Present	Joyce et al. (2004)
Global Precipitation Mission	0.1°	90 N - 90 S	30 minutes	Mar 2014 - Present	Smith et al. (2007)
PERSIANN	0.25°	50 N - 50 S	6 hours	Mar 2000 - Present	Hong et al. (2004)

2.2 Evapotranspiration

Evapotranspiration (ET) is affected by a number of processes at the interface between soil, vegetation and atmosphere. ET plays an important role in the redistribution of water and any change in ET can greatly affect a catchment's water balance (Mauser and Schädlich, 1998). Remotely sensed estimates of ET generally involve the use of a land surface model that transforms a combination of in-situ and remote sensed data into evapotranspiration estimates (Kustas and Norman, 1996). However, while remotely sensed estimates of ET may not give actually ET, it provides an estimate which can be correlated with actual ET.

Table 2 lists two popular datasets of ET. While many more exist we will only briefly described these two. MODIS ET is derived from the Moderate Resolution Imaging Spectroradiometer, MODIS observations use the Penman-Monteith equation to compute global ET (Mu et al., 2011). MODIS is a NASA instrument aboard two satellites that provide global coverage every 1-2 days across a range of wavelengths (Barnes et al., 1998). MODIS ET provides estimates of ET at 8-day, monthly and annual rates with a spatial resolution of $1km^2$. GLEAM –Global Land surface Evaporation: the Amsterdam Methodology (Miralles et al., 2011) produces a coarser (0.25° ~ 25km at equator) daily global estimate of ET compared with MODIS ET. GLEAM uses a modified Priestly-Taylor model and estimates evaporation for: bare earth; short vegetation; and vegetation with a tall canopy.

Table 2: Characteristics of most widely used evapotranspiration satellite products

Mission	Resolution	Latitude Extent	Temporal Scale	Time Period	Reference
MODIS ET	1 km	90 N - 90 S	8 days	2000 - 2010	Mu et al. (2011)
GLEAM	0.25°	90 N - 90 S	Daily	1980 - 2011	Miralles et al. (2011)

2.3 Soil Moisture and Water Storage Change

Soil moisture is one of the critical components in hydrological modelling. Soil moisture strongly affects the amount of precipitation that is infiltrated or converted to surface runoff. While remote sensing of surface/soil moisture has a long history in research, this is not the case for applications, mainly due to the difficulties in reliable implementation and integration of remotely sensed estimates of soil moisture in hydrological models.

Estimates of soil moisture can be derived from both active (radar) and passive (most popular) platforms. Active platforms illuminate the surface with their own energy and record the reflected signal while passive systems record the reflected energy from the Sun. Active platforms consist of either Synthetic Aperture Radar (SAR) or scatter-meters and while SAR can provide fine spatial resolution (~1km at global scale and better than 25 m in some case studies), scatter-meters can provide near global coverage at 50 km squares from the ERS-scatterometer and at 25 km squares from the Metop-A scatterometer data at a temporal resolution of a few days (Figure 2 and Table 3). Both are available from TU-Vienna (http://rs.geo.tuwien.ac.at/data-viewers/) and produce soil moisture content between 0% and 100% relative to a dry and wet reference (Wagner et al., 1999, 2007).

Passive platforms primarily consist of the AMSR-E instrument on–board ESA's Soil Moisture and Ocean Salinity (SMOS) mission and NASA's Soil Moisture Active Passive (SMAP) (Table 3). SMOS was launched in 2009 and aims to provide estimates of soil moisture every 3 days with 4% accuracy (Barré et al., 2008; Kerr et al., 2001). SMAP was launched January 2015 and has near global coverage with the same temporal resolution as SMOS (Entekhabi et al., 2010). While SMOS will have a spatial resolution of approximately 50 km, SMAP data will be available at 40 km for the radiometer data and 1 km for the SAR data. One drawback of remote sensing of soil moisture is that the signal only responds to the top 5 cm soil layer; however, methods are available to estimate the top 100 cm (Wagner et al., 1999). These methods involve filtering the surface soil moisture content with an exponential function.

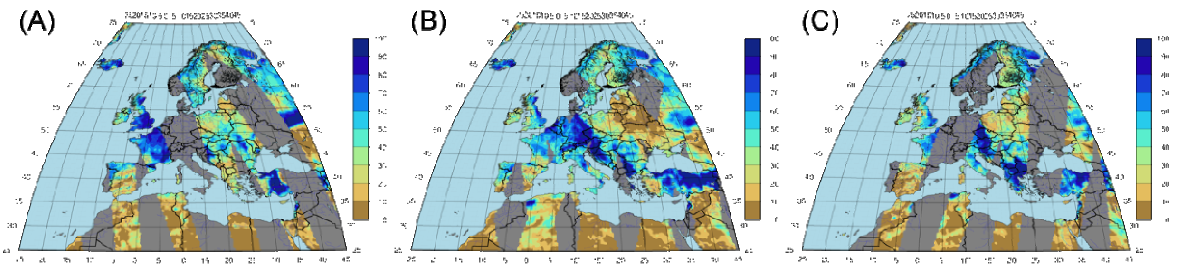

Figure 2: ASCAT (Metop –A) 25km soil moisture obtained for: (A) 02:10 on 07/10/15; (B) 02:10 on 08/10/15; and (C) 14:10 on 08/10/2015.

Satellites also have the ability to track change in water storage. For remote sensing this includes all forms of water stored above and below the Earth's surface. The Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004) in operation since March 2002 provide monthly maps of Earth's gravitational fields from which changes in total volumetric water storage can be inferred, including water stored as snow, soil moisture and ground water. GRACE data has been used to model the total water storage changes at continental and large river basin scales (eg. Amazon and Congo Basin) (Crowley et al. 2006, Syed et al. 2008). However, due to the large footprint of GRACE (10^{o} ~ 110 km at equator) the use of GRACE for Irish catchment may not be feasible or suitable. Figure 3 shows the long term total water storage change (cm) over the entire island since March 2002 (Swenson, 2012).

Table 3: Characteristics of most widely used soil moisture and storage change (GRACE) satellite products

Mission	Resolution	Latitude Extent	Temporal Scale	Time Period	Reference
ERS	50 km	90 N - 90 S	35 days	Nov 1978 - Present	Wagner et al. (1999)
Metop-A	25 km	90 N - 90 S	5 days	Jun 2012 - Present	Wagner et al. (2010)
SMOS	50 km	90 N - 90 S	1-3 days	Jan 2010 - Present	Entekhabi et al. (2010)
SMAP	1-40 km	90 N - 90 S	1-3 days	Jan 2010 - Present	Kerr et al. (2001)
GRACE	1^{o}	90 N - 90 S	Monthly	Mar 2002 - Present	Tapley et al. (2004)

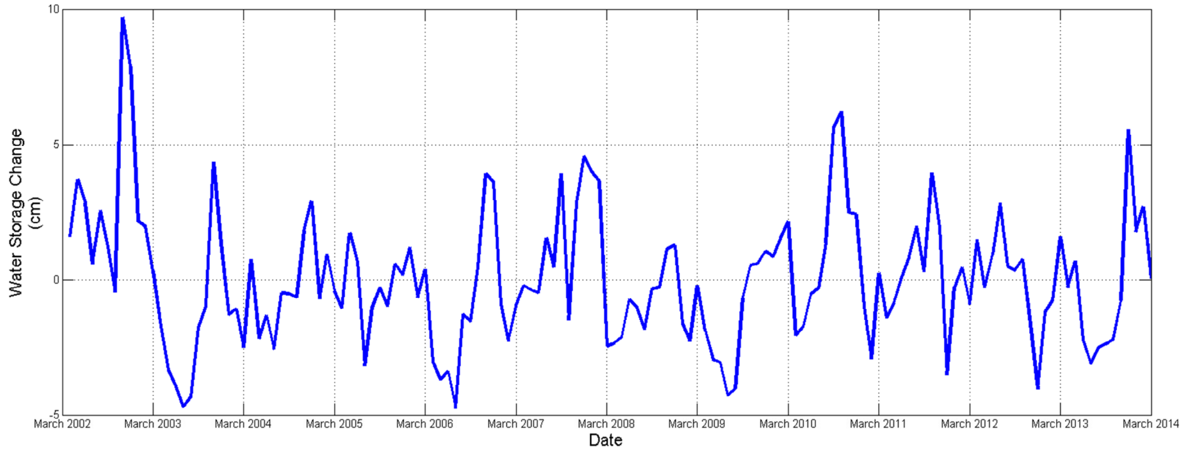

Figure 3: Total water storage change (cm) from the long term mean since March 2002 estimated for Ireland from GRACE Data

3. SATELLITE MISSIONS FOR MONITORING

3.1 Water Surface Height

At present there exists no satellite mission that can measure either surface runoff or river discharge; however, river discharge may be more suitable to remote sensing than surface runoff as discharge is generally confined to rivers with particular characteristics, such as width (section 3.2), surface slope, water level and channel depth, which may be measured or inferred by remote sensing. The use of satellite altimetry (radar or laser) data to measure water surface height of reservoirs and lakes is widespread (Birkett et al, 2011). However, the use of satellite altimeters in the measurement of water levels for rivers is less common and has focused mainly on large river whose widths are greater than 1 km (Alsdorf et al., 2007; Frappart et al., 2006; Hall et al., 2012). This is mainly due to the fact that to-date no altimetry mission has focused on inland waters and therefore their ground footprint is generally too large to see any except the largest rivers, because to avoid contamination of the signal the river width needs to be approximately three times the ground footprint (Birkett et al.,2002). Table 4 lists the most widely used satellite altimeters used in water resources. However, of these missions, only ICESat's ground footprint is sufficiently small to sense any river or water bodies in Ireland. A new database created by O'Loughlin et al (in review), found that 384 single observations were obtained over Ireland during the ICESat operationally period. This is expected to change in the future with the planned missions of ICESat 2 and the Surface Water Over Topography (SWOT) missions (section 4). However, as Ireland has a very good hydrometric collection programme in place, these missions may provide only little additional information for Irish hydrology.

Table 4: Comparison of most popular altimetry missions for estimating surface water height

Satellite Mission	Ground Footprint (m)	Repeat Cycle (days)	Time Period	Accuracy (m)
TOPEX/Poseidon	~600	9.9	1993-2001	0.35 (Frappart et al. 2006)
ERS-2	~400	35	1995-2003	0.55 (Frappart et al. 2006)
Enivsat	~400	35	2002-2012	0.28 (Frappart et al. 2006)
ICESat	~70	-	2003-2009	0.10 (Urban et al. 2008)
SARAL	~200	35	2013 -Present	0.04 (Verron et al. 2015)

3.2 Surface Water extents

One area where remote sensing generally outperforms in-situ measurements is in deriving areas and extents of both permanent water bodies and flood inundation areas. Obtaining these areas and extents can be undertaken with most satellite imaging platforms. This is especially true for mapping permanent water bodies; however, obtaining flood extents is fairly opportunistic and atmospheric conditions, such as persistent cloud cover, may restrict data acquisition to a small number of remote sensing platforms not dependent on the visible light spectrum, such as microwave sensors. Generally, surface water extents can be successfully measured with a variety of visible band sensors (eg. Landsat, MODIS, SPOT, Sentinal-1) with different spatial and temporal resolutions and by SAR imagery (eg. RADARSAT, JERS-1 and ERS) (Table 5). However, their routine application is limited (Alsdorf et al., 2007).

Optical (visual band) sensors suffer from a number of limitations including: cloud cover; low spatial resolution for sensor with high temporal resolution (MODIS); and the inability to detect extents beneath vegetation. Despite these limitations, when conditions are suitable, water extents can be successfully derived using a very simple methodology (e. g. Jung et al. 2011; O'Loughlin et al 2013, Trigg et al 2012).

Microwave (SAR) sensors, unlike optical sensors, have the ability to penetrate both clouds and rain. This is highly advantageous for mapping flood extents as bad weather and cloudy conditions are highly correlated with flood events. They can also acquire images during hours of darkness and map water extents under vegetation to some degree, unlike optical sensors. In the past ten years there have been significant advances in the use of SAR in inundation extent mapping (eg. Matgen et al., 2007; Mason et al., 2010; Giustarini et al., 2013). While the processing of SAR images is slightly more difficult than optical images, the European Space Agency (ESA) provides free software for processing SAR images.

Table 5: Comparison of popular satellites for surface water extents and land-use change

Satellite Mission	Sensor	Ground Footprint (m)	Repeat Cycle (days)	Time Period	Reference
Landsat	**Optical**	15 +	16	1972 - Present	Behrens (2009)
MODIS	**Optical**	250 +	1	1999 - Present	Barnes et al. (1998)
SPOT	**Optical**	1.5 +	26	1986 - Present	Chevrel et al. (1981)
JERS-1	**Optical &SAR**	18	44	1992- 2001	Raggam et al (1996)
ERS	**SAR**	30	35	1991 - 2003	Attema et al. (1991)
RADARSAT	**SAR**	1 - 100	24	1995 - Present	Parashar et al (1993)
Sentinal-1	**SAR**	5	12	2014 - Present	Attema et al. (2008)
TerraSAR-X	**SAR**	1 - 16	11	2008 - Present	Werninghaus (2004)

3.3 Land-use Change

One of the most useful applications of remote sensing is the monitoring of land-use change. The research literature contains numerous examples of the optical sensors, listed in Table 5, used to detect land-use change over time (e.g. Seto et al., 2002; Deng et al., 2009; Justice et al., 1998). Of the optical sensors, the Landsat missions are the most widely used due to their relatively small spatial resolution, short repeat cycle, and longevity as well as their being available free of charge. Landsat's mission satellite was launched in 1972 and the latest (Landsat-8) launched in 2013. The US government has also stated that there will always be a Landsat satellite in operation, guaranteeing an ever increasing database of Earth surface imagery.

4. FUTURE SATELLITE MISSIONS AND HYDROLOGY

As previously mentioned there is no satellite dedicated exclusively to hydrology. This will change with the planned Surface Water Over Topography (SWOT) mission, due to be launched in 2020. SWOT is designed to make the first-ever global survey of Earth's surface water and is a joint collaboration between NASA and the French space agency (CNES). SWOT will consist of two SAR antennae that are expected to perform with centimetric errors when sampled to 1 km^2 (Bates et al 2014). SWOT will produce water level estimates for lakes greater than 250 x 250 m^2 and both water level and discharge estimates for rivers greater than 50 m wide twice every 21 days (Durand et al. 2010). SWOT is not designed to replace existing discharge measurement networks but as a complimentary source of additional information.

5. CONCLUSION

This paper is a brief review of a small number of hydrological applications that remote sensing from space can be used for. To-date, most satellite missions have not focused on hydrology; however, many missions from different fields provide useful sources of information. In the Irish context, the use of many of the existing satellites is not possible due to a number of factors. These factors include: no coverage in the case of many precipitation missions; the ground footprint of many satellites being larger than many Irish rivers and catchments, as in the case of water level estimation and water storage change. The two fields where satellite remote sensing is valid in an Irish context is the mapping of flood extents and in monitoring land-use change - two fields which seem to have been overlooked. As satellites become more accurate and footprints shrink, the use of remote sensing satellite data in an Irish context will increase. This is especially true with the launch of SWOT when it will become possible to monitor the majority of Irish lakes and some rivers from space.

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