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SATELLITE SEA LEVEL MEASUREMENT:A REVIEW OF CURRENT TECHNIQUES

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ABSTRACT

The measurement of sea level is quite important for sea navigation safety, bathymetric survey, marine engineering, military purposes and climatic studies. In climatic studies sea level is an indication to know if the oceans are rising or falling over time and to what extent is this rise or fall. Coastal cities would surely be affected if oceans and seas are rising significantly. Melting glaciers and global warming among other weather changes caused by man are main causes of an overall rise in sea level. For its high importance and strategic values, sea level has been monitored by hydrographers for about 200 years. Tide gauges, which are water-level recorders were the instruments used for thisjob for almost all this period. Only recently, new sea level measuring techniques are invented and used for recording sea level, especially at places where it is difficult to install conventional tide gauges. These new techniques include acoustic gauges, pressure gauges, radar gauges, global positioning systems gauges and satellite altimeters. In contrast to the sparse network of coastal tide gauges, measurements of sea level from space bysatellite altimetry provide near global and homogenous coverage of the world's oceans. The present paper is an attempt to give an introduction about importance, causes and effects of sea level rise and to review satellite techniques used for sea level measurements. A brief history of the development of satellite techniques and a comparison with tide gauges regarding difficulties, problems and limitations facing each will be investigated and outlined.

KEYWOEDS: Satellite altimetry; sea level; climate change; global warming; tide gauges; hydrographers; navigation.

INTRODUCTION

The sea level has been monitored for a long time mainly for navigation safety and for other reasons including effects of ocean rise on coastal cities. That is because considerable rise in sea level would surely cause hazard and risk to people living in such areas (Passeri, 2015). The number of coastal cities form almost two thirds of world mega cities (the U. N. Atlas of the Oceans show that eight of the ten largest cities in the world that have relatively high population lie near a coast) with inhabitants more than one billion people threatened by sea level rise (Nicholls, et al, 2010; Church et al, 2011; Lindsey, 2016). Millions of people will be affected bycoastal flooding during the current 21st century. This number will be considerably reduced if appropriate planning and adaptation measures are taken care of (Church et al, 2011). Another effect of sea level rise is to increase recession of the world sandy beaches which will affect an important human recreation facility.

The average level for the surface of oceans is usually referred to as sea level, or mean sea level (MSL). The MSL is adopted as the datum for measuring elevations of points on the earth's surface, hence for production of topographic or contour maps, digital terrain models and waterdepth on nautical charts (Bradshaw et al. 2016).

Sea level monitoring also provides key data for coastal authorities responsible for the determination of property boundaries, and for planners and engineers in the construction of waterfront buildings, bridges, and jetties. It is a fundamental parameter in the fields of oceanography and geophysics. Data from water level measurements are also used by hydrographers to compute water flow in rivers and water volumes in lakes.

Some other important applications of studying sea level include: fish industry where fishes usually move in the direction of tidal waves, ship industries where high sea levels may obstruct reaching shallow estuaries, coastal erosion (Lindsey 2016), design and building of coastal defenses against flooding, tectonic plates movements and vertical ground motion (Cozannet, etal. 2015; Passeri, 2015) and shoreline erosion (Passeri, et al, 2015).

Water level monitoring was used to be done manually with tidal gauges fixed at selected sea coasts. Now it has been improved to be done remotely and much more regularly where data canbe sent to data collecting centers over great distances.

Sea level variation over a long period is also considered important for coastal habitation and research related to studies of global climate changes. It is one of the 50 Essential Climate Variables (ECVs) listed by the Global Climate Observing System (GCOS) in climate change monitoring (Ablain, et al, 2015).

Causes and Rate of Sea Level Rise

Researchers have pointed out that one of the main causes of sea level rise is global warming that causes increase in sea water temperature and hence thermal expansion of the upper water surface layer. Another and more important cause of sea level rise is the melting glaciers and ice sheets that add water to ocean leading to increase in its volume (Noerdlinger and Brower, 2007). A comparative study by Jevrejeva, et al. 2008 showed that glacial volume changes and ice sheet melting in Greenland and Antarctica make up the leading component, almost double the effect of the thermal expansion. This is confirmed by Shum et al, 2008 who showed that sea level rise (1900-2007) due to Antarctic, Greenland, Glacier and Thermosteric contributions are respectively, 0.49mm/year, 0.76mm/year, 0.80mm/year and 0.16mm/year.

Sea level varies slightly up and down from year to year, although the general trend is rising up as observed by sea level measuring instrument as stated by Church and White, 2011 and shown in Figure 1.

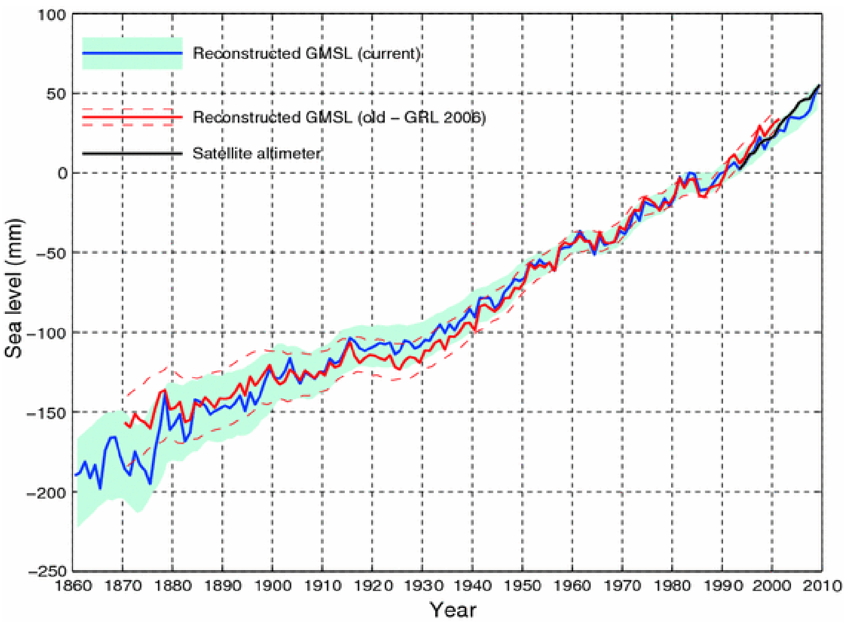

Fig. 1: Sea Level Rise Trend (Church and White, 2011).

Church and White (2011) used satellite altimeter data for 1993-2009 in addition to coastal and inland sea level data from 1880 to 2009 to estimate the rise in global average sea level.

They have derived the rise rate of sea level as 3.2 mm/year from the former and 2.8 mm/year from the latter, while the total global sea level rise from 1880 to 2009 is about 210 mm. The same results were obtained by Boening, et al, 2012, Cazenave, et al, 2012 and Hay, et al, 2015.

Levitus, S., et al. 2012 used historical data from the World Ocean Data Base 2009 to derive estimates of change of ocean heat content and the thermosteric component of sea level change ofthe 0-700 and 0-2000 m layers of the World Ocean for 1955-2010. They found out that the thermosteric component of sea level trend was 0.54mm/year for the 0-2000 m layer and 0.41mm/year for the 0-700 m layer of the World Ocean for 1955-2010. Lindsy, 2016 also statedthat in 2014, global sea level (GSL) was 67mm higher than the 1993 average. Sea level rises at arate of 3.2mm/year due to melting glaciers and thermal expansion of sea water.

Tsuji et al, 2016 estimated annual rate of area of land emerged since 1905 in the area of Albany River in Canada to be approximately 3.0km^2/year and that land will continue to emerge with a rate of 1.4km^2/year over the next century. Kopp, et al, 2015 have studied relative sea level (RSL)trajectories for North Carolina, USA and concluded that RSL rise was fastest (~7 mm/yr) during the early Holocene and slowed over time with the end of the deglaciation.

Although tide gauges were the main source of information about sea level for two centuries, sea level has been routinely measured from space using satellite altimetry techniques during the last two decades (Ablain, et al, 2015). Since the beginning of the 1990s, sea level is routinely measuredusing high-precision satellite altimetry.

In the following sections basic principles and historic development of satellite sea level measurement techniques will be outlined.

Principles of Satellite Altimeters

Altimetry satellites determine the height of the ocean surface with respect to a reference such asthe average global sea level (known as the Earth's "geoid"). Orbiting altimeters make very precise measurements of the ocean's surface topography. Advanced dual band radar altimeters are used to measure height from satellite to sea surface (H). This measurement coupled with orbital elements augmented by GPS, allows determination of water surface topography. Two different wavelengths of radio waves allow the altimeter to automatically correct for varying delays in the ionosphere. Figure 2 is a sketch showing principle of Satellite Altimetry (Davis, 2013). A pulse-limited radar is used to measure the altitude of the satellite above the closest point of the sea surface, *R*. Global precise tracking along with orbit dynamic calculations are used to determine the height of the satellite above the ellipsoid, *H*. The difference between thesetwo measurements results in the sea surface height, *h* given as; h= H (Davis, et al 2013).

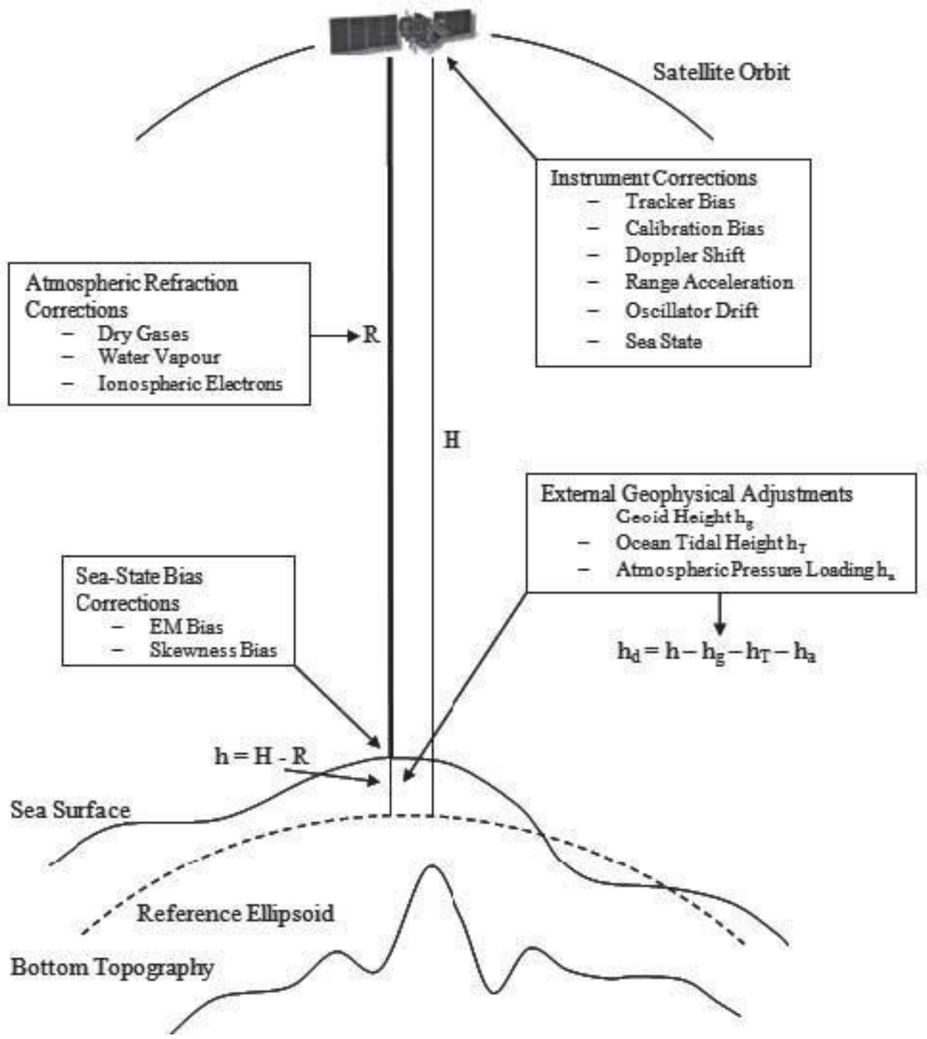

Fig. 2: Principle of Satellite Altimetry (Davis, et al, 2013).

However, accurate estimates of *R* and *H* are not sufficient for oceanographic applications of altimeter range measurements. The sea surface height, *h* relative to the reference ellipsoid is the superposition of a number of geophysical effects. In addition to the dynamic effects of geostrophic ocean currents that are of primary interest for oceanographic applications, h is affected by undulations of the geoid, *hg* about the ellipsoidal approximation, tidal height variations, *hr* and the ocean surface response to atmospheric pressure loading, ha. These effects on the seasurface height must be modelled and removed from *h* in order to investigate the effects of geostrophic currents on the sea surface height (Chelton et al., 2001). Thus the sea level, h is given as:

$$h = H - R + \sum \Delta R_j - h_g - h_r - h_a$$

Attaining the required sub-millimetre accuracy for sea level rise monitoring, is challenging and requires satellite orbit information, geophysical and environmental corrections and altimeter range measurements of the highest accuracy. It also requires continuous satellite operations overmany years and careful control of biases (Church, et al, 2011).

Historic Development of Satellite Altimeters

America's first experimental Space station, Skylab, was launched in May 1973. It carried active and passive microwave measurement system called S193. This instrument carried the first spaceborne altimeter to study ocean effects on pulse characteristics. Using a pulse width of 0.1 microseconds this system was able to achieve a resolution of 15 m, from 435km altitude.

Geodynamics Experimental Ocean Satellite (GEOS 3) was launched in April 1975, and ended its mission in December 1978. It carried the first instrument that produced useful measurements of sea level and its variability over time. When a satellite flies at higher altitudes, this reduces the strength of the altimeter's return and changes the size of the footprint on the ground. Since then all altimeters have used pulse compression to enhance the resolution. GEOS 3 offered significant improvements over Skylab's altimeter as far as performance and coverage width.

SEAfaring SATellite (Seasat) was launched bythe National American Space Agency (NASA) in June 1978, from an altitude of 800km and ended its mission in October 1978, due to a malfunction. One of the instruments it carried was a radar altimeter to measure ocean surface height (www.altimetry.info/missions/past-missions/seasat/). GEOdetic SATellite (Geosat) was also launched by NASA in March 1985, and ended its mission in January 1990. It was the first mission to to provide long-term high-quality altimetry data. For the first time, a long-term global view of sea level change has become available to the ocean science community. The U.S. Navy's GEOSAT altimeter satellite has been measuring ocean surface topography with unprecedented precision since March 1985. GEOSAT represents a dramatic improvement over earlier observations from NASA's SEASAT mission primarily because of higher spatial resolution and longer temporal duration (3+ years vs. 3 months), as depicted on the cover of this issue. The measurement of sea level is an important variable in the determination of ocean circulation.

Ocean observation was one of the purposes of the ERS-1 Satellite mission built by Eurepean Space Agency (ESA), launched in July 1991 and switched off in June 1996. The mission carrieda radar altimeter to observe earth and ocean from an altitude of 785km.

In August 1992, the Topex/Poseidon (T/P), a joint project between NASA and the French Space Agency (CNES), was launched from an altitude of 1336km. Two radar altimeters and precise orbit determination system were included in the mission. It can be considered as the foundation for long-term ocean monitoring from space. It provided satellite mission observatios of sea level change from 1992 to 2005. In September 2002, the mission took a new orbit while its previous one was overflown by a new mission Jason-1 that ended in January 2006. During these years it measured sea levels better than 5cm acxcuracy.

In April 1995, ERS-2 was launched bay ESA as the follow-on from ERS-1, with a one-day shift. It carries several instruments including radar altimeter. Since 22 June 2003, ERS-2's onboard tape recorder used for the altimeter data has experienced a number of failures. This means that altimeter data are unavailable except for when the satellite is within visibility of ESA's ground stations over Europe, North Atlantic, the Arctic and western North America. In July 2011, ERS-2 was brought down to a lower orbit. These deorbiting procedures are done while the fuel is still sufficient to make the careful manoeuvres.

ERS-1 and ERS-2 were followed on by Enviromental Satellite (Envisat) to observe Earth's atmosphere and surface, also equipped with radar altimeter.

Jason-1 was launched in late 2001 as the successor to T/P It continued this record by providingan estimate of global mean sea level every 10 days with an uncertainty of 3-4 mm. During its first six months of flight, the Jason-1 satellite was placed along the same ground track as T/P, about one minute apart. Because the two satellites observed nearly identical ocean conditions, scientists could then calibrate the new instruments on Jason-1. Once scientists confirmed that Jason-1 was taking measurements with equal or better accuracy than its predecessor, T/P was manoeuvred into a parallel groundtrack to increase coverage between the two satellites.

Although the payload instruments of Jason-1 were in nominal health the contact with the spacecraft was lost on 21st of June 2013. All attempts to re-establish communications with the Jason-1 spacecraft over the ten days from 21 June to 01 July, from both US and French ground stations, were unsuccessful. Jason-1 was passivated and decommissioned on 01 July 2013, terminating the Jason-1 mission after 11.5 years of operations.

Current Satellite Missions

Jason-2 was launched on 20 June 2008 with the purpose of taking over and continuing the missions of T/P and Jason-1, in the framework of a cooperation between CNES, NASA, Eumetsat and NOAA. It carries the same kind of payload as its two predecessors for a high-precision altimetry mission (2.5cm).

Jason-2 flies in a low-Earth orbit at an altitude of 1336 km. With global coverage between 66°N and 66°S latitude and a 10-day repeat of the ground track, Jason maps 95% of the world's ice- free oceans every ten days. The main instruments on Jason-2 are:

- The Poseidon-3 dual frequency altimeter and its antenna used to measure sea surface height, wind speed, and significant wave height; it is the primary instrument onboard Jason-2 and was supplied by CNES
- The Advanced Microwave Radiometer (AMR), which measures disturbances due to water in the atmosphere; it was developed at NASA's Jet Propulsion Laboratory (JPL)
- Three systems for determining the satellite's precise location in orbit: the Doppler Orbitography and Radio-positioning Integrated by Satellite package (DORIS), developed by CNES, the Laser Retroreflector Array (LRA, supplied by NASA), and the Global Positioning System Payload (GPSP) receiver (designed by NASA/JPL)

Fig. 3: Jason 2 Satellite, www.bing.com/images.

Cryosat-2, an altimetry satellite, was launched on 8/4/2010 with an altitude 717km and inclination 92^o. It was built by the ESA and dedicated to polar observation. It embarks on a three-and-a half-year mission to determine variations in the thickness of the Earth's continental ice sheets and marine ice cover, and to test the prediction of thinning Arctic ice due to global warming. It carries Synthetic Aperture Interferometric Radar Altimeter (SIRAL) and DORIS instrument but no radiometer.

SIRAL is a Ku-band instrument (13.575 GHz) operating in three modes

– Low-resolution, nadir-pointing altimeter mode
– SAR mode
– SAR interferometer mode

DORIS is a satellite tracking system designed by CNES as a new system to provide precise orbits on-board low Earth orbit satellites

Jason-3 is the fourth mission in U.S.-European series of satellite missions that measure the height of the ocean surface. Launched on January 17, 2016, with altitude 1336km and inclination 66^o, the mission will extend the time series of ocean surface topography measurements (the hills and valleys of the ocean surface) begun by the T/P satellite mission in 1992 and continuing through the Jason-1 and the currently operating OSTM/Jason-2 (launched in 2008) missions. These measurements provide scientists with critical information about circulation patterns in the ocean and about both global and regional changes in sea level and the climate implications of a warming world (Kelly, D., 2016). The primary instrument deployed on Jason-3 is a radar altimeter that can track variations in sea level down to a few centimeters. The type of high-resolution data that it collects will aid scientists around the world in research and weather forecasting. The measurements will also help shipping vessels that need accurate oceanographic data to make their voyages, as the satellite's sensors can track the speed and direction of ocean currents.

The altimeter measures sea-level variations over the global ocean with very high accuracy (as 1.3 inches or 3.3 centimeters, with a goal of achieving 1 inch or 2.5 centimeters). Continual, long- term, reliable data of changes in ocean surface topography will be generated and will be used by scientists and operational agencies (NOAA, European weather agencies, marine operators, etc.) for scientific research and operational oceanography for the benefit of society.

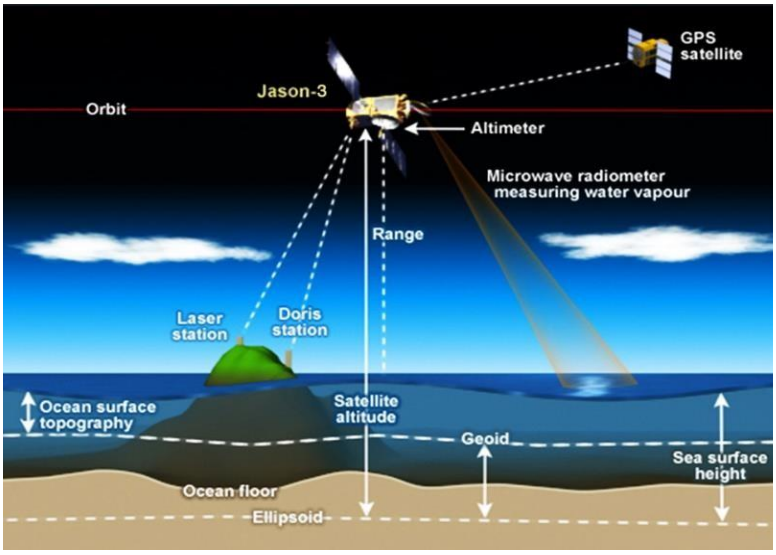

Fig. 4: How Jason-3 Works https://www.nesdis.noaa.gov/jason-3/mission.html.

Jason-3 continues the international cooperation, with NOAA and Eumetsat leading the efforts,along with partners NASA and CNES.

Scientific Instrument(s)

- Altimeter
- Microwave radiometer
- DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite)
- Laser Retroreflector Array (LRA)
- Global Positioning System (GPS) receiver

Spaceborne radar altimeters have proven to be superb tools for mapping ocean-surface topography, the hills and valleys of the sea surface. These instruments send a microwave pulse to the ocean's surface and time how long it takes to return. A microwave radiometer corrects any delay that may be caused by water vapor in the atmosphere. Other corrections are also required to account for the influence of electrons in the ionosphere and the dry air mass of the atmosphere. Combining these data with the precise location of the spacecraft makes it possible todetermine sea-surface height to within a few centimetres.

Once the Jason-3 Satellite retires in three to five years, scientists plan to launch another satelliteto continue the mission of building a satellite record of sea level rise on Earth.

Josh Willis, Lead Project Scientist for the Jason-3 mission at NASA's Jet Propulsion Laboratory said rising sea levels were one of the factors that contributed to the destruction wrought by Hurricane Katrina in 2005. Hundreds of people died and the storm surge devastated gulf coast communities as Katrina became one of the deadliest storms in recent U.S. history.

Raney, 2001 suggested that if built with delay-Doppler radar altimeter technology, the Water Inclination Topography and Technology Experiment (WITTEX) satellites which consist of three TOPEX-Class radar alternative would be sufficiently small that all three can be launched simultaneously by one vehicle. WITTEX will provide near-simultaneous and accurate measurement of sea surface heights along three parallel tracks, providing oceanographic data not previously available.

The accuracy of altimetry-based sea level records at global and regional scales needs to be significantly improved. For example, the global mean and regional sea level trend uncertainty should become better than 0.3mm/year and 0.5 mm/year, respectively (currently 0.6 mm/year and 1–2 mm/year). Similarly, interannual global mean sea level variations (currently uncertain to2–3 mm) need to be monitored with better accuracy (Ablain, et al, 2015).

The recent launch of new altimetry missions (Sentinel-3, Jason-3) and the inclusion of data from currently flying missions (e.g. CryoSat, SARAL/AltiKa) may provide further improvements to the important climate record (Kelly, 2016; Ablain, et al, 2017).

Ablain, et al, 2015 used a new processing system with dedicated algorithms and adapted data processing strategies in order to reduce orbit errors and wet/dry atmospheric correction errors, instrumental drifts and bias, intercalibration biases, intercalibration between missions and combination of the different sea level data sets, and an improvement of the reference mean seasurface.

Satellite Altimetry compared to Tide Gauges

- **Universality**

All local tide gauges measure change in sea level relative to the land surface. This means that data recorded represent both the change in absolute sea surface height and the change in local land levels. The main advantage of satellite altimetry over tide gauges is the ability to measureabsolute sea level, independently of land movements, and the possibility to eliminate mass redistribution signals due to its nearly global spatial coverage.

In contrast to the sparse network of coastal and mid-ocean island tide gauges (Float, acoustic, Radar, Pressure, GPS), measurements of sea level from space by satellite radar altimetry provide near global and homogenous coverage of the world's oceans, thereby allowing the determinationof regional sea level change.

- **Accuracy**

Deana and Houstonb, 2013 used 456 monthly tide gauge records to compare their results with those of satellite altimetry for the period (1993 to 2011). They concluded that the average trendof the 456-gauge sets agree well with trends based on satellite data, being 3.26mm/year and 3.09mm/year respectively.

Jeverejeva, etal, 2014 used 1277 tide gauge records since 1807 to provide an improved global sea level reconstruction and analyse the evolution of sea level trend and acceleration. They havefound a good agreement between the rate of sea level rise (3.2 ± 0.4 mm/year) calculated from satellite altimetry and the rate of 3.1 ± 0.6 mm/year from tide gauge-based reconstruction for theoverlapping time period (1993–2009). The new reconstruction suggests a linear trend of 1.9 ± 0.3 mm/year during the 20th century, with 1.8 ± 0.5 mm/year since 1970. Regional lineartrends for 14 ocean basins since 1970 show the fastest sea level rise for the Antarctica (4.1 ± 0.8 mm/year) and Arctic (3.6 ± 0.3 mm/year).

Table 1: Comparison of Sea Level change rates for tide gauge and satellite altimetry (Jaggan andDavis, 2012), From: Davis, et al, 2013.

Station Location	Sea Level Change Rates (mm yr^{-1})		Differences (mm yr^{-1})
	Tide Gauge	Satellite Altimetry	
Sabine Pass, Texas	4.58	3.87	0.71
Port Iasabel, Texas	7.14	7.80	0.66
Apalachicola, Florida	3.55	4.45	0.90
Clearwater Beach, Florida	7.88	7.86	0.02
Key West, Florida	6.09	6.34	0.25
Grand Isle, Louisiana	3.27	3.18	0.09
Isabela De Sagua, Cuba	0.97	0.85	0.12
San Juan, Puerto Rico	-1.92	-1.07	0.85

The fact that the speed of sound is temperature dependent, requiring precise temperature-dependent corrections to the measured range, limits the accuracy of acoustic tide gauges.

Cipollini, et al, 2017 carried out comparative study along the UK coast and could demonstrate good agreement between coastal altimetry and tide gauge observations, with root mean square differences as low as 4 cm at many stations.

- **Practicality**

Float gauges are difficult to install, requiring a 'stilling well', and, while they can be adapted to provide real-time digital data by means of shaft encoders or potentiometers, they do not necessarily measure the same level as the outside water if installed in estuaries. They also tend tobe labour-intensive, requiring frequent maintenance of float mechanisms and clearing of sediment accumulation in the well. Unlike satellite altimeters other tide gauges such as acoustic, pressure, radar and GPS need to be installed and some of them also need maintenance too.

The main constraint for radar gauges is that the power consumption may be relatively large in radar systems if used on a continuous basis in a rapid sampling mode. Averages are typically taken over periods of minutes. This may limit its use in some applications (e.g. tsunami warning) where observations are required on a continuous high-frequency (e.g. 15-second) basis.

Also for radar tide gauges, a structure above water is necessary for the transducer to be referenced vertically. Although this structure does not need to be sophisticated because the acquisition and processing system can be protected in a shelter at some distance from the measurement location an additional work is needed.

The site at which a tide gauge is to be installed and fixed should be selected according to: safety stability and access of installation area. Sites such as river estuary or near outfalls or where ships pass should be avoided. Local benchmarks and mains power should be in a neighbouring area.

All these condtions are not necessary for satellite altimetric sea level measurement.

The two types of sea level data (relative and absolute) complement each other, and each is usefulfor different purposes. Relative sea level trends show how sea level change and vertical land movement together are likely to affect coastal lands and infrastructure, while absolute sea level trends provide a more comprehensive picture of the volume of water in the world's oceans, how the volume of water is changing, and how these changes relate to other observed or predicted changes in global systems (e.g., increasing ocean heat content and melting polar ice sheets). Tide gauges provide more precise local measurements, while satellite data provide more complete spatial coverage. Tide gauges are used to help calibrate satellite data.

For more discussion of the advantages and limitations of each type of measurement, see Cazenave and Nerem (2004).

- **Future Prospects**

Satellite altimetry has provided two decades of near global, continuous sea level data. However, while consistent and reliable data is available, altimetric data is based on the open ocean and its weakness lies in coastal measurements and monitoring. A vertical reference system must be localized as local factors infl uence its determination. Hence, satellite altimetry derived data alone is not sufficient to effectively and accurately determine mean sea level.

CONCLUSIONS

- The paper overviewed importance, causes, applications and effects of sea level changes together with the history and development of satellite altimetric technique of measuring sea level. It has been ended with comparative study of altimetric sea level measurement with other tide gauges methods.
- Satellite altimetry technique for measuring sea level has been developed and used worldwide through the last two decades. The technique has the advantage of covering water surfaces worldwide and hence sea level data can be given in absolute value for any point on the water surface of the globe.
- Availability of sea level data from satellite altimeter worldwide makes it handy for researchers and other users.
- Accuracy of data from satellite altimetry competes well with tide gauges. Further improvement in processing would lead to better accuracy as recommended by different researchers such as Cipilloni, et al, 2017.

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