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STWS: a Space borne Tsunami Warning System using GNSS-Reflections – a feasibility study

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ABSTRACT

The mission objective is to design a Space Borne Tsunami Warning System (STWS) that uses GNSS Reflections (GNSS-R). The GNSS-R technology is an experimental technology, but has the advantage that it only needs a passive measurement system. A key requirement is to be competitive with the Deep Ocean Reporting of Tsunamis (DART) system. Competitive is defined in warning time, coverage and costs. A satellite based warning system offers by definition the possibility of a global system. The system is designed having 40 satellites in a 60:40/12/12 Walker constellation. This number combined with characteristics of the constellation ensures a global coverage with a worst case warning time of 44 minutes after a Tsunami event has been triggered. The satellites measure the reflected GNSS signals with a phased array antenna with digital beamsteering. For data relay intersatellite communication is chosen, in this way all satellites can make contact with the ground stations right away. The cost price of the STWS is estimated at €491 million, which is more expensive than DART, but alternative uses have not been taken into account yet.

1. Introduction

On December 26*th* 2004 a devastating disaster struck the island of Sumatra and other countries around the Indian Ocean. A large earthquake of 9.0 on the Richter scale triggered a massive Tsunami in the Pacific Ocean, killing over 250,000 people. In reaction to the disaster many humanitarian and research projects were started and expanded. One of the fields of research is the design and construction of a global system to detect Tsunamis in order to give an early warning signal to the population in threatened areas.

At this moment a working warning system is expanded to cover the Indian Ocean, in addition to the already covered Pacific Ocean. This system is called the Deep-ocean Assessment and Reporting of Tsunamis (DART) system [1] and is based on the use of deep ocean pressure measurements. These pressure measurements can be converted to sea level heights, and this information can be used to warn for a Tsunami. This is by definition a local system that currently only covers a part of the US West Coast.

This paper will focus on the detection of Tsunamis using a space-borne satellite constellation, since this would provide global coverage, and could prove more effective than the DART system. To ensure low costs and mass of these satellites, focus will be on the use of Global Navigation Satellite System Reflections (GNSS-R). This results in a passive system to measure the important parameters.

The requirements are defined such that the Space borne Tsunami Warning System (STWS) can compete with the DART system in respect to the costs and warning time. If such a system would be possible in theory, a demonstrator mission has to be designed and flown, in order to prove the technical feasibility of the still experimental GNSS-R technology.

2. Background

2.1 Tsunamis

Tsunamis are large waves (wavelength, λ>25km) that can be generated by many different mechanisms including submarine earthquakes, landslides, submarine volcano eruptions and meteoroid impacts.

Earthquakes that create a significant vertical seabed displacement are by far the most common cause. When the seafloor moves up or down, the water column above is displaced and its potential energy changes. After generation, the oceanic disturbance spreads out in all directions. Since horizontal displacement caused by the earthquake has little influence on the Tsunami, it is difficult to accurately correlate Tsunami magnitude to earthquake magnitude. However, experience shows that life threatening Tsunamis are usually caused by earthquakes with a magnitude of 7 or higher on the Richter scale. Tsunamis travel very fast, while experiencing very little energy loss in deep waters. Typical velocities of a Tsunami can reach up to 1000 km/h.

Efforts toward a quantification of Tsunamis started about 75 years ago by the pioneering work of Sieberg [2]. There is no single Tsunami quantification method that is widely agreed upon. In 1942 and 1956 work by Imamura and Iida [2] related the magnitude of the Tsunami to wave height at the coast. Numerical modeling by Gica and Teng [3] related the run up height above mean sea level (MSL) at the shore (Figure 1) to the height of a Tsunami in open sea. Run up heights are strongly influenced by bottom geometry near the shore. Very steep changes in depth near the shore result typically in great run up heights, while gradually changing bottoms allow the Tsunami to dissipate a lot of energy and result therefore in smaller run up heights. Based on the literature a run-up height of 1 m is defined as dangerous [4]. For an average coastline this corresponds to a significant wave height of 10 cm [4]. Therefore a wave detection height of 10 cm will be a key requirement for the satellite constellation.

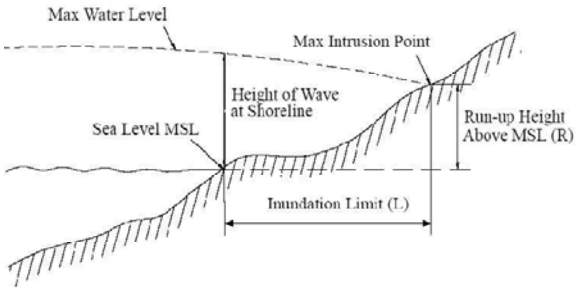


Figure 1: Definition of run up height and inundation limit [3]

2.2 GNSS-R

The Global Navigation Satellite Systems Reflections (GNSS-R) system is a passive, precise, long-term, all-weather, multi-purpose and wide coverage system. Therefore, it forms a potential and powerful technology for remote sensing applications.

Among several, two classes of applications of GNSS-R have rapidly emerged in the scientific community: sea surface altimetry, which aims at retrieving the mean sea level like classical radar altimeters do, and sea-surface reflectometry for the determination of sea roughness and near-surface winds.

GNSS-R is a form of passive, bistatic radar. GNSS satellites emit signals that reflect on the Earth's surface (oceans). These reflected signals are picked by a satellite receiver in Low Earth Orbit (LEO). The scattering points on the surface span an area of scale approximately equal to *2h*, where *h* is the altitude of the satellite. This basic principle is shown in Figure 2. Therefore a GNSS-R detection system would act as a very wide-swath altimeter, which improves measurement capability of existing altimeters and provide multiple tracks of the observed phenomena.

A key advantage of GNSS-R is its multistatic character, as shown in Figure 2. Unlike monostatic systems, a single GNSS-R receiver is able to collect information from a simultaneous set of reflection points associated with different GNSS emitters. A system in LEO capable of collecting GNSS signals would potentially combine more than twenty reflection tracks at the same time (GPS, GLONASS and Galileo).

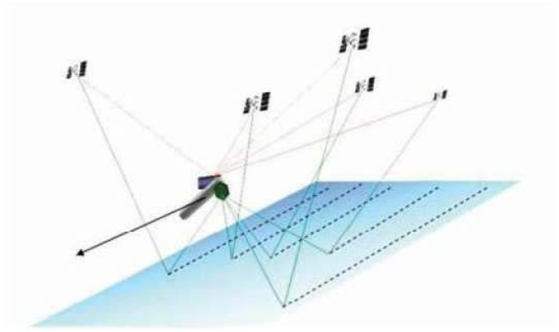


Figure 2: The multistatic GNSS-R concept: The GNSS-R signals emitted from diverse GNSS satellites [5]

The major advantage of this property would be the improvement of the quality of the mesoscale altimetry. GNSS-R would make mesoscale measurements of the sea surface height better, since important parameters as resolution, swath-width, frequency of visits and long-term stability will be improved with respect to conventional altimeters. Mesoscale measurements constitute an important missing element from the Global Climate and Ocean Observation System (GCOS/GOOS). Moreover, GNSS-R altimetry makes the detection of major Tsunamis possible, due to its higher spatial and temporal resolution with respect to conventional altimeters.

Another important aspect is that GNSS was originally designed for navigation and positioning purposes and not for radar applications. Therefore the reflected signals are weak, however they can be detected and contain a lot of useful information. Recently, in 2005, GPS-R L1 C/A signals have been successfully detected in space by the UK-DMC mission, using a moderate antenna gain of 11.8 dBiC [5].

The reflection process affects the signal in several ways, at the same time degrading and loading it with information from the reflection surface. Normally, the amplitude will be reduced, the waveform shape distorted and the coherence mostly lost. Signals scattering from off-specular locations arrive later than the ones from the specular. It should be recalled that a specular point provides the shortest path.

Altimetry in GNSS-R can be carried out in two general ways. In code altimetry the code is used for ranging with the direct and reflected signals. In phase altimetry, the phase is used. An important difference with normal GNSS processing is that the reflection process affects the reflected signal. This process generally distorts the triangular waveform shape after correlation of the return and submits the reflected signal very incoherently. The basic principle of *code* GNSS-R altimetry, as depicted in Figure 3, is that the reflected wave arrives later than the direct one, since it will travel a longer distance to the receiver.

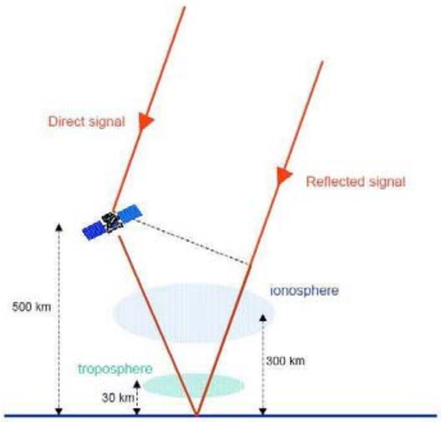


Figure 3: The principle of altimetric GNSS-R: The path difference between the direct and reflected signal is proportional to the altitude [6]

At low altitudes the path difference, is proportional to the altitude, over the reflecting surface and the local elevation of the satellite as seen from the specular point.

The arrival time difference is called lapse. Uncertainty in the lapse translates rather directly into altimetric uncertainty. The altimetric error is related to the lapse precision. This parameter depends on four terms:

1 Delay precision of the direct waveform
2 Delay precision of the reflected waveform
3 Ionospheric error
4 Tropospheric error

This allows to calculate the accuracy for the STWS and which code (C/A or P) should be used for Tsunami detection.

3. Requirements

The mission statement for the project is defined as: “To design a feasible and competitive GNSS-R based space borne Tsunami early warning system”.
The mission statement is the natural top level requirement. From this the key requirements follow, which comprise of the driving and killer requirements. The most important requirements are listed in Table xx.
The first key requirement is that use must be made of GNSS-R technology. This results in the requirements for the receiving antenna and it limits the height of the constellation of satellites. Reflected GNSS signals are extremely weak and place therefore high demands on the receiving equipment.
Second, the system should be competitive with respect to its competitors. In this case there is one main competitor, the Deep-ocean Assessment and Reporting of Tsunamis (DART) system.
Third the system needs to deliver a warning in time so that the endangered population is warned and evacuated in time. This is a killer requirement. A warning time of 30 minutes is defined, in this timeframe the tsunami needs to be detected, the data confirmed and the population evacuated. This requirement determines to a large extent the size of the constellation needed.
Several other requirements are defined like coverage between latitudes of -60 and 60 degrees; this is because in this band most Tsunami inducing earthquakes take place. The system should be available at least 99.9% of the time to avoid the missing of Tsunamis. The false alarm rate should be kept as low as possible, since a false alarm will incur considerable economic losses.

Table 1: STWS Requirements

Use GNSS-Reflections	
Cost	Competitive with DART
Tsunami detection height	<10 cm
Warning time	<30 min
Warning	>98% *endangered* people
Coverage	-60<lat<60
Life time	>20 years
Availability	>99.9%
False alarm rate	<once in 3 years

4. System design

To allow for design in parallel the space-borne Tsunami system is split up in 6 parts.

- Payload
- Orbit & constellation
- Satellite bus
- Data processing
- Data link
- Launch method
- Warning methods & sequence

For all parts, several design options have been analyzed. The complete warning system concept is the result of the tradeoffs of sub segment design options. The tradeoff criteria followed directly from the listed requirements. A detailed description can be found in [4].

Satellite payload

It is important that the GNSS-R antenna has sufficient gain. Since this is a killer requirement, the design option of a single antenna which has unacceptably low gain is immediately discarded. The mechanical beamsteering antenna has lower reliability and higher complexity than the digital beamsteering antenna. Although the latter concept has higher power consumption, this is the only disadvantage with regard to mechanical beamsteering. It does have higher reliability and higher gain and since the power is expected not to be a limiting factor, the digital beamsteering antenna is chosen as best concept.

Orbit & Constellation

In order to detect the GNSS reflections with sufficient signal strength, a Low Earth Orbit (LEO) was chosen. The orbit decay rate and the environmental radiation level are important factors for the orbit design. Circular orbits, with an altitude of 645 km, were selected for the STWS. Simulation of the temporal coverage of a Walker 60:40/10/2 constellation (Figure 4) indicated that a total of 40 satellites is sufficient. A significant decrease in detection time can be obtained by constellation optimization. A maximum *detection* time of 30 minutes is expected to be possible with a constellation of 40 satellites.

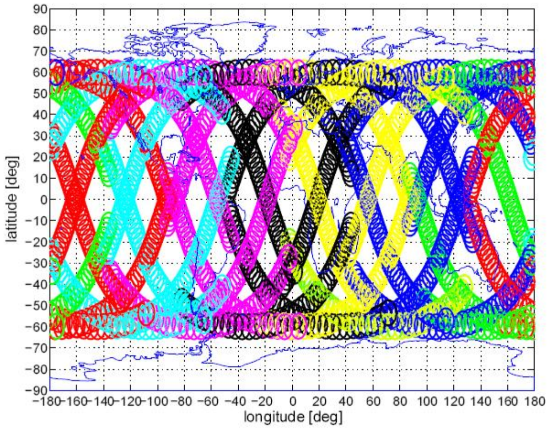


Figure 4: Walker 60:40/10/2 constellation

Satellite Bus

The most important aspect of the satellite bus is to provide the support for the GNSS-R antenna. The antenna needs to facing the Earth all time.
Therefore the satellites will have a three axis stabilization system which consists of momentum and reaction wheels. Thrusters will be used for momentum dumping, orbit maintenance and the de-orbit burn at the end of life. The power will be provided by solar arrays, which will be mechanically pointed towards the sun.

Data Processing

On board the satellite, the data will be pre-processed. Processing only on the ground is not feasible as this requires unacceptable data rates. Processing all data on board up to and including the decision to warn for a Tsunami is also not possible, since a large amount of information is needed that is only available on ground (eg. Precise GNSS positions). Although this information could be uplinked to the satellite, it is more effective and reliable to process this information on the ground. Preprocessing on board of the satellite minimizes the amount of data to be sent.

Data link

Because the reaction time needs to be as short as possible, it is very undesirable to be dependent on direct satellite-to-ground communication only. The use of a relay satellite to have a continuous data flow to the ground is reliable but expensive and since cost is important, the use of intersatellite communication is chosen. There will always be several satellites in sight of a ground station to link down the observation data of the other satellites.

Launch Method

Because the STWS satellites will be small, a dedicated launch per satellite will be unnecessarily costly. Using a dedicated launch for all satellites at once is risky and has big consequences for the required ∆V budget of the satellites. Piggy back launches are not a realistic option because of the number of satellites to be put into orbit, and the short time span available for implementation. The option of launching multiple satellites at once with a dedicated launcher proves to be the best option and is therefore selected.

Warning methods & sequence

A Tsunami warning signal can be broadcast using different techniques. A large variety of warning distribution methods is required to alert as many people as possible and as soon as possible. The time to reach the public is critical and will take a significant part of the time frame. The used methods at a specific region are most likely to be selected by the authorities of that country. It is assumed that the warning needs to go via the authorities since they are responsible for the consequences of evacuations. Authorities will use different methods for broadcasting of the Tsunami signal for redundancy. Methods already used at this moment are sirens and emergency alert broadcasting (AM and FM radio and television), but SMS text messaging might also form a possibility.
The time it takes to distribute the warning and inform the authorities and institutes is estimated on 6 minutes.
Future warning methods include using the services of EGNOS and the ALIVE concept.

A more thorough and detailed description of the concepts can be found in [4] and [7].

5. Perfomance analysis

Tsunami detection height
In this section the altimetric accuracy, i.e. the accuracy of the sea level height measurements, will be analyzed. As it is explained in the introduction, the altimetric error is a function of the lapse error,σ_l and the elevation angle,ε of the signal.

$$\sigma_h = \frac{\sigma_l}{2 * \sin \varepsilon}$$

The lapse error can be expressed as follows:

$$\sigma_l^2 = f_{iono} * \sigma_R^2 + \sigma_D^2 + \sigma_{tropo}^2$$

The delay errors of the direct and the reflected signal can be obtained from the following equation [6]. In this equation, τ_{chip} is defined as the chip length (300 m for the C/A code and 30 m for the P code) and SNR_v is defined as the one-shot signal-to-noise ratio.

$$\sigma_R = 0.22 * \frac{\tau_{chip}}{SNR_v}$$

According to [6], the SNR_v for the direct signal is assumed to be equal to 10 and the SNR_v for the reflected signal is assumed to be equal to 4.7. Further, the integration time of the direct signal is set to 10 ms and 0.8 ms for the reflected signal [6]. If a sampling time of three seconds is used to analyze the altimetric performance of the signals [6], then the SNR_v after 3 seconds of the direct signal will be equal to 640.
For the reflected signal the SNR_v will be equal to 290.

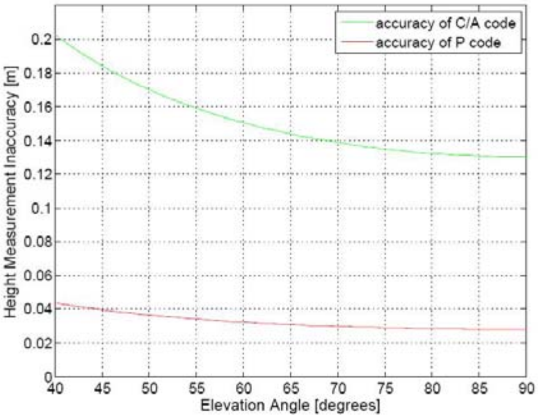


Figure 5: Altimetric error as function of the elevation angle

Figure 5 shows the altimetric precision as function of the elevation angle for the C/A code and the P code, respectively.
From this figure follows that the C/A code is not accurate enough to satisfy the requirement imposed on the sea level height measurements, namely an accuracy of 10 cm. On the other side, it is shown shows that the P code satisfies the sea level height requirement, and hence Tsunamis can be observed. Because of the high precision obtained, the P code measurements can also be used for mesoscale altimetry.

Time constraints
The Tsunami Warning System is designed to provide a *warning-to-the-user-signal* for a tsunami within 30 minutes after the triggering of the event takes place. This requirement is a heavy constraint on the minimum number of satellites. The concept of the Walker constellation with 40 satellites yields at this moment in a worst case scenario a *detection time* of 30 minutes. This is the time from the event taking place till the moment one of the satellites measures the Tsunami. The detection time includes verification with other available data like seismic measurements. After the event is verified a warning message will be sent to the informing authorities and institutes. These will then warn the endangered people using the methods described before. By this time a total of 44 minutes has passed.

Coverage
The constellation has been designed in such a way that the coverage is maximal over the region that experiences the largest number of Tsunami inducing Earthquakes. The consequence is that the Polar Regions are not covered. However it is still possible to measure Tsunamis induced in that region. Tsunamis induced in the polar areas make only a very small percentage of the total of the world wide Tsunamis. Tsunamis originating in the polar areas are rarely life-threatening, since these regions are not densely inhabited.

Other requirements
A prediction of the false alarm rate cannot be performed at this stage, although it was required to be once in 3 years. It can only be analyzed when Tsunami intensity models are setup and investigated. The availability of system greatly depends on the redundancy of

the satellites. That is the probability that when one or more satellites malfunctions the rest of the satellites are able to correct this. The probability that a satellite fails is determined by its instrument characteristics. The availability yet remains to be determined. The percentage of endangered people that can be warned in time depends on the methods used for the warning and on the responsiveness of the warning authorities. This needs further investigation and development.

Cost

Cost Estimation of DART

DART is a Tsunami warning system making use of buoys deployed in the Pacific Ocean. The comparison of costs with the STWS is difficult since the both systems are fundamentally different. At this time the DART system is not global and there are no plans known at the moment to make it global, therefore cost estimations are not available. But to assess the competitiveness of the STWS an estimation for the cost of a global DART system must be made. Since the late 1990's the DART buoys are placed at a cost of €225.000 a piece and a maintenance cost of €135.000 including shipping time [8]. When all the 53 planned buoys are deployed in the Pacific, Caribbean and the Atlantic oceans, all of the coasts of the United States of America will be covered [1]. This is about equivalent to coverage of one third of the total earth.

Above mentioned prices result in a investment cost for global coverage of about €36.000.000 and a yearly maintenance cost of about €21.600.000 [8]. Over a lifespan of 20 years this results in a total life cycle cost of about €468.000.000. It must be noted that this estimation is not unambiguous since it is not known whether it is necessary to place approximately the same number of buoys in all oceans. The costs for the DART system are given in FY2006 Euros; the breakdown is shown in figure 6.

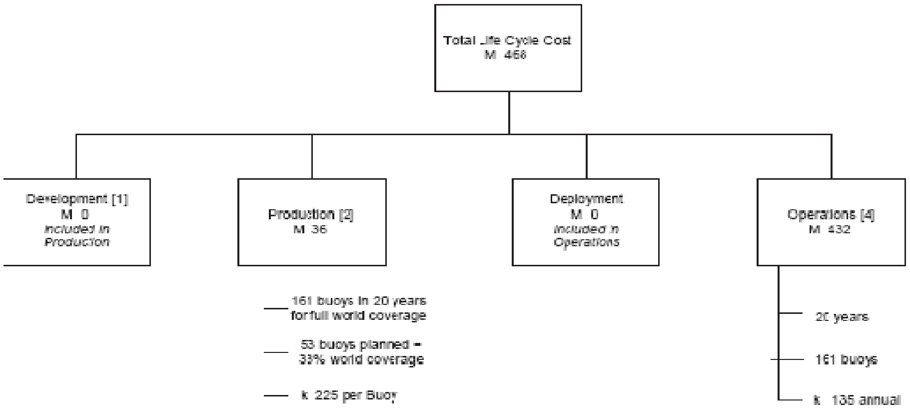
Cost Estimation of STWS

The total Life Cycle Cost (LCC) of the STWS consists of development, production, launch and operational costs, see Figure 6. The total LCC is estimated on €540.000.000 for a period of 20 years. This estimation is based on the assumptions and derivations mentioned below. The costs are presented in FY2006 Euros.

Development costs

In the estimation of the development some assumptions are made:

- The development period is estimated to about 3 years
- The number of employees is
- estimated to be about 25 FTE average during the development period
- The labor costs of the design employees is estimated on an average of €136.000 a year



Sources:
1. Development according to references (FY2004 DART Buoy network program plan, FY2005 DART Buoy network program plan) included in production cost.

2. Production costs include production and development

3. Deployment cost according to references (FY2004 DART Buoy network program plan, FY2005 DART Buoy network program plan) included in operations.

4. Operations include maintenance, shipping time, deployment and data handling.

Costs normalized to FY2006 Euro

Besides the labor costs of the employees, facilities for the design and testing need to be taken into account. This is estimated at €1.600.000

Summing the above mentioned costs, the total design costs are estimated at €11.800.000.

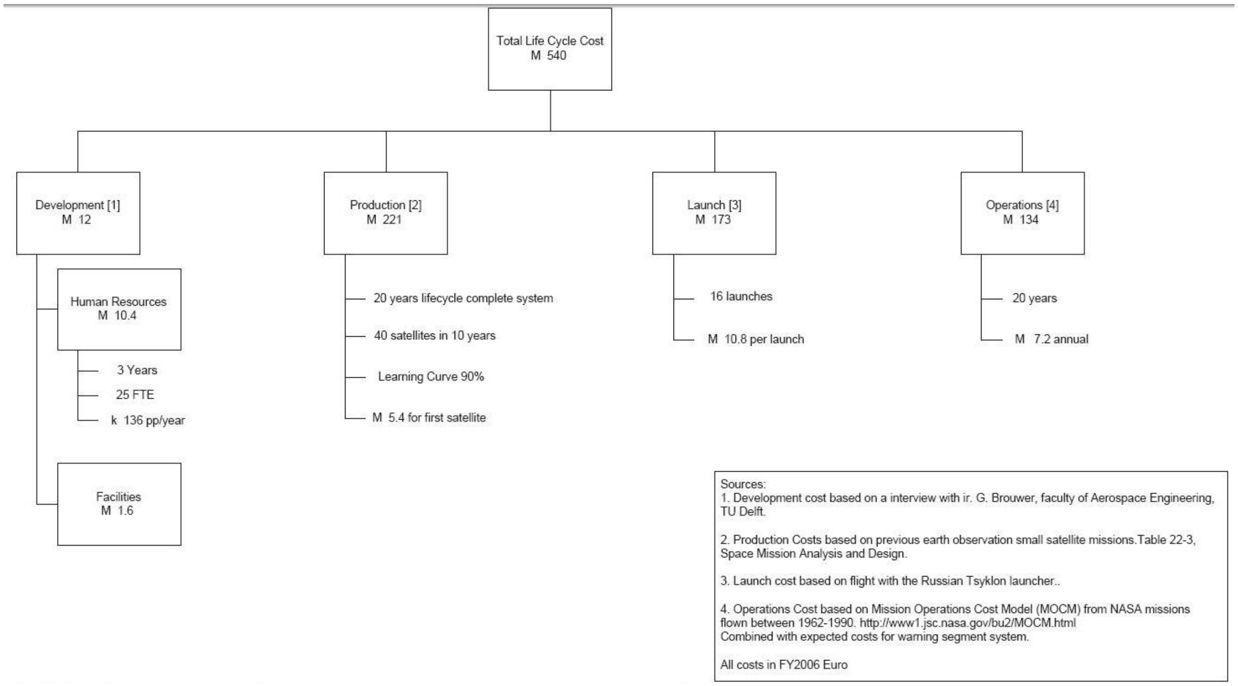
Production Costs
The production cost of one satellite is estimated on €5.400.000. This is based on satellites with comparable weight and orbit characteristics [9]. The lifetime of satellite is limited due to the atmospheric drag, which is 5000 days (13 years) for an altitude of around 600 km.
The lifetime used in the cost estimation is set to 10 years. For a constellation of 40 satellites 80 satellites have to be produced for a life cycle of 20 years.
Taking into account the learning curve the production cost of 80 satellites in 20 years will be significantly less.
Using learning curves, the production cost of 80 satellites is estimated at €221.500.000.

Launch costs
In the estimation of the costs of the launch a few assumptions are being made:

- All the satellites can be launched in groups of 5. The satellites will then drift into the desired orbits. More satellites is possible from a launch point of view, but since the constellation has a lot of different orbital planes, the fuel budget to move the satellites into the different planes would be huge.
- The launcher assumed to be used is the Russian Tsyklon, with an expected launch cost of about €9.600.000 [9] Political factors that often determine the country of origin of the launcher have not been taken into account at this stage.
- Not taken into account here is the possibility that the satellites might survive longer than expected or that a satellite fails before its intended end of life.

The total launch cost is expected to be €172.000.000.

Operational Costs
The operational costs are estimated for a period of 20 years. Using the NASA cost estimation model [10] the operational costs are estimated on €7.200.000 per year, this results in a total cost of €134.000.000. In this cost also costs for operating the warning segment have taken into account. This comprises mainly of data analysis at the ground.
It is clear that at this moment the STWS is expected to be more expensive. There are cost savings possible to reduce the gap of €72.000.000. These savings may be in the launch segment, possibly also in the satellite segment. This will become clearer in the



Sources:
1. Development cost based on a interview with ir. G. Brouwer, faculty of Aerospace Engineering, TU Delft.

2. Production Costs based on previous earth observation small satellite missions.Table 22-3, Space Mission Analysis and Design.

3. Launch cost based on flight with the Russian Tsyklon launcher..

4. Operations Cost based on Mission Operations Cost Model (MOCM) from NASA missions flown between 1962-1990. http://www1.jsc.nasa.gov/bu2/MOCM.html
Combined with expected costs for warning segment system.

All costs in FY2006 Euro

further design of the satellites. A demonstrator will give an indication of the satellite costs; however this is not a driver for the design of the demonstrator satellite.

6. Conclusions and Recommendations

In principle, the GNSS-R based space borne Tsunami Warning System is a feasible alternative to the DART system for detecting Tsunamis. The system would use the signals of opportunity, the GNSS Reflections; a proper phased array antenna needs to be designed for this purpose. The constellation would consist of 40 satellites orbiting the earth in a 60:40/12/12 Walker constellation. The satellites will make use of inter-satellite communication to relay measurements back to the ground stations. The estimated worst-case warning time is 44 minutes. This timeline stretches from the moment the Tsunami event occurs till the warning of the endangered population. The costs for the space borne system will be higher than the DART system at €491 million. This difference might be reduced if the satellites could serve alternative uses, e.g. altimetry [4].

To test the experimental GNSS-R technology a demonstrator mission is recommended. In previous studies a design has been made for such a demonstrator satellite [4] [7]. This satellite will be different from the final satellites since the phased array GNSS-R antenna is still considerable large at this moment in time. A more detailed description and design can be found in [7].

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