Bachelor thesis

How to determine position, rotation and orientation for a tethered twin nano satellite with sufficient accuracy to map data from an interferometer.

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Abstract

Nanosat projects pose a relatively cheap and flexible method to obtain knowledge of space, the universe and the technologies needed for future investigations. One of the current frontiers is low frequency radio astronomy. On Earth LOFAR (Low-Frequency Array) is measuring these signals, however the atmosphere, ionosphere and interference make space a better place for measurements especially for frequencies below 30 MHz. TwenteSat is a nano satellite student project which aims to bring two satellites in low Earth orbit (LEO) attached to each other by a tether and together forming an interferometer. The practical, technological and measurement knowledge obtained may be used for future projects such as the OLFAR (Orbital Low Frequency ARray). TwenteSats' satellite system will initially start as one satellite (10x10x30cm) and once in orbit change to two 10x10x10cm units connected by a tether. The interferometer will use two dipole antennas and is therefore direction sensitive. These antennas will be in line with or parallel to the tether and thereby have a donut shaped radiation sensitivity pattern with the tether in the middle of the donut. Rotation will be used to hold the nanosats apart by centrifugal force thereby also rotating the direction of the measurement. In order to map the data it is therefore necessary to know the orbit altitude, satellite system rotation and the satellite system orientation relative to Earth. To determine these parameters the usage of GPS, measurements from Earth and measurements on the nanosat itself will be discussed in general. These measurements will be conducted such that it is not necessary to know the altitude before they take place. In this paper different system level approaches to determine these variables will be discussed for a nanosat platform.

I. INTRODUCTION

An increasing amount of space research is being done by students in relatively cheap missions. Most of these missions are based on the cubesat platform[1] and many are aimed at enhancement of the technology for this platform. Some examples are antenna setups, tethers[2] and GPS tracking[3] for cubesats. Besides improvement of the technology, new methods of using satellites such as swarm satellites[4] are becoming increasingly interesting. However, while facing these challenges TwenteSat will also provide for a science mission.

The TwenteSat student project[5][6] is a cubesat mission with the goal of measuring low frequency (300 kHz to 30 MHz) astronomical signals which cannot easily be measured on Earth. In order to measure these low frequencies with a high angular resolution one needs either a very large dish or an interferometer setup as proposed in the OLFAR project[7][8][9].

In order to get a first feeling for what to expect with an interferometer in space, TwenteSat will use two measurement nodes (cubes) separated by about 100 m. This distance will be maintained by a tether held tight by the rotation of the entire satellite system. Due to the directional sensitivity of the interferometer it is important to know the orbit, but also the orientation of the rotation plane with respect to Earth, the rotation angle and potentially the pitch, roll and yaw of each cube with respect to the tether, at the time of measurement. Extra attention must be paid to the distance between the two nodes as this as an impact on the correlation delays for beamforming.

In this paper a study will be presented on how to determine the position of a nano-satellite (1 to 10 kg) consisting of two nodes connected by a tether. The relevant parameters are the orbit, the distance separating the nodes and their orientation, which must be determined with sufficient accuracy to map data from a space based interferometer.

In section II of this paper a description will be given of the TwenteSat mission LOAS (Low frequency Astronomical Satellite). In section III of this paper a reference system for the spacecraft is proposed to enable the efficient description of the relevant variables which must be measured for LOAS. In section IV the available sensors are discussed with their individual (dis-)advantages. Section V will contain different design options for the setup of these sensors. Finally the conclusion and suggestions for further work will be given in section VI.

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II. LOAS MISSION

The main goal with LOAS (Low frequency Astronomical Satellite) is to build the first interferometer in space. In order to achieve this students are building the first scientific student satellite in the Netherlands and facing a lot of technological issues at the forefront of space technology. However some of the more basic building blocks can be reused or bought. For as far as possible the satellite will be build from commercial components (COTS). Subsystems required for interferometry are shown in figure 1.

The satellite will measure low frequency (<100 MHz) at two different positions to perform interferometry. This requires two antennas with appropriate filtering and amplification. Next the signals have to be correlated and be provided to researchers.

To correlate the signals they must be mixed either on Earth or on the satellite. Doing the correlation on the satellite has the advantage of reducing the downlink requirements to Earth but does require inter-satellite communication to get the two signal together.

Regardless of where the processing is done an up and down link to earth are required. The uplink to provide updates and commands from earth, the down link to receive measurements from the satellites sensors. Bringing the total amount of antennas up to at least three per node, uplink, downlink and interferometer antenna and preferably a fourth for inter-satellite communication as described in[10].

The correlated signal by itself does not contain all the information on what was measured. In order to determine if the signal is from Earth or a particular direction in space it is necessary to know the attitude of the satellite. How this can be achieved is the topic of this paper.

All of this requires electrical power, therefore power generation, distribution and possibly storage will be necessary. There are two conventional power generation methods, solar panels and nuclear power, another interesting power generation method is possible with an electrically conductive tether.

Solar panels are the most common power generation method and are widely available. However their efficiency is related to the angle between the panels and the sun and will generate no power at all when behind Earth.

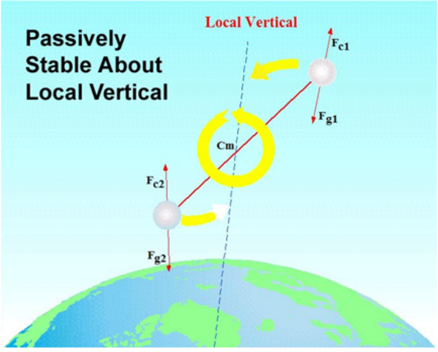

Figure 2: Impression of how tidal locking works.

Nuclear power does not have these limitations, however nuclear power has some mayor enviromental issues[11], and will therefore not be considered further.

Generating power with an electrodynamic tether is still experimental, though theoretically possible, it has not yet been applied successfully in space. The principle applied is that the Earth magnetic field can be used to induce a current in a conductive loop moving though its field. A drawback of this method is the loss of orbit speed due to the generation of power.

Beside these electrical subsystems there are also physical and mechanical issues which must be addressed. The relevant ones are the thermodynamics and the mechanics of the structure, tether and antennas along with an information distribution system on Earth.

The thermodynamics are of importance to this paper because the components used may not work, or break down faster if the system gets to warm or changes temperature to fast. Another consideration is that the tether will probably change length with changing temperatures. The expected temperature range is between the plus and minus 100 degrees Celsius[11].

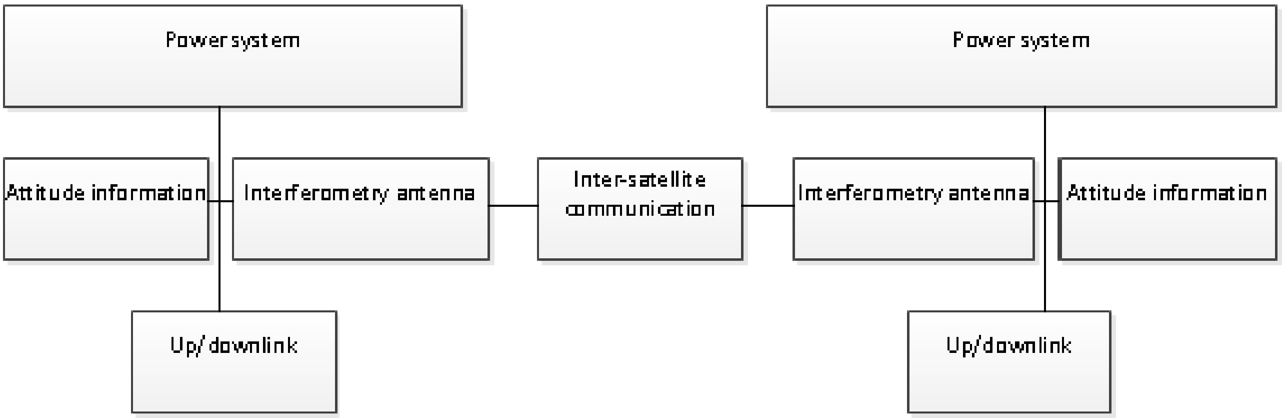

Figure 1: Overview interferometer system.

The mechanics of the structure must provide for the deployment of the tether into a stable rotating satellite system. A special case of this rotation is tidal locking as seen in Figure 2, source [12] . Two bodies orbiting at different heights have different speeds, the lower body moves father than the higher body. As a result, when they are connected to each other, the lower body must decelerate and the upper body accelerate. This leads to a stable situation where they are both on the local vertical.

A problem however is how the tether can be deployed. An easy method would be to rotate the satellite before tether deployment, release a latch and let the tether unroll itself using the rotation energy. Assuming the rotation energy just before seperation of the nodes is equal to the rotation energy when the seperation is maximum an estimate is made how fast the satellite must initialy rotate.

$$
\begin{aligned}
&E = E_1 = E_2 \\
&E = \tfrac{1}{2} * I * \omega^2 \\
&\tfrac{1}{2} * I_1 * \omega_1^2 = \tfrac{1}{2} * I_2 * \omega_2^2 \\
&\omega_1 = \sqrt{\tfrac{I_2}{I_1}} * \omega_2 \\
&I_1 = \tfrac{M_{total} * L_1^2}{12} \\
&I_2 = \tfrac{M_{tether} * L_2^2}{12} + \tfrac{M_{node1} * M_{node2}}{M_{node1} + M_{node2}} * L^2 \\
&\omega_1 = 0.53\text{Hz}
\end{aligned}
$$

Where E is rotation engergy,
I is the moment of inertia,
ω is the rotation speed
ω_2 is the rotation speed at tidal locking (1.05 mHz) M_{total} is the satellite mass (3Kg)
M_{tether} is the tether mass (1Kg)
$M_{node1} \& M_{node2}$ are the node masses (both 1 Kg)
L_1 is the length of the satellite before seperation (0.3m)
L_2 is the length of the satellite after seperation (100m)

The specifications for LOASs attitude determination are:

- Knowledge of relative possition nodes with accuracy of at least 30 cm over a 10 second measurment periode
- Power consuption of less than 2 W per node
- Space needed onboard smaller than 400 cm^3 per node
- Knowledge of measurement direction

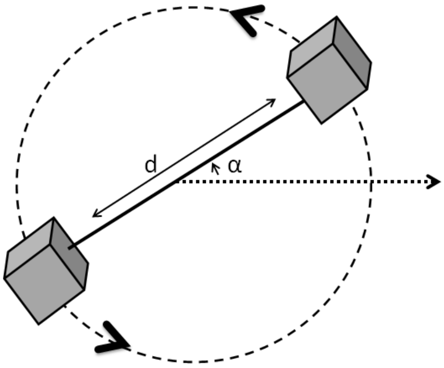

Figure 3: Impression of satellite with two cube measurement nodes connected by a tether, however not on scale as the tether is 100m and the cubes have sides of 10 cm

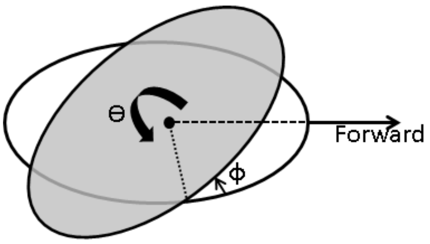

Figure 4: Rotational plain of the satellite with defining angles θ and ϕ

III. REFERENCE SYSTEM

TwenteSat will consist of two 10x10x10 cm observation nodes rotating around their (combined) centre of mass, while connected to each other by a tether as shown in Figure 3. The satellite will start in a lost in space situation with the constraint of being in Earth orbit. To describe the orbit it is common practice to use Kepler coordinates. With the orbit of the satellite's centre of mass described it is still necessary to describe the rotation of the satellite around its own axis, bearing in mind that the satellite has a rotation plane along the tether.

It is expected that the rotation plain will be along the local vertical. Due to this orientation with respect to Earth this position will be used as a base for the reference together with the forward direction of the satellite. The orientation of the satellite can be modeled by two angles θ and ϕ, analogue to respectively the longitude of the ascending node and the inclination, as shown in Figure 4.

The position and orientation of the satellite can be described which leaves only the position of the measurement nodes and their individual orientations (pitch, roll, yaw). Their position will be described by the angle between the node and the forward orbital direction and the distance separating the nodes, see Figure 3, which will only be constant if the tether does not change length. The expectation however is that the tether will form a mass spring system leading to small fluctuations and, depending on the tether implementation, expansion due to temperature fluctuations. Temperature fluctuations are expected to be in the range of $+/-100\,^{\circ}$.

Due to the rotation of the nodes the centrifugal force will direct the node such that the axis from where the tether is attached through the centre of mass will remain on the same line as the tether itself, Figure 5, reducing variations in pitch and yaw. However a small variation cannot be ruled out and must therefore still be measured. The roll is not limited by the tether until the tether itself becomes twisted enough to

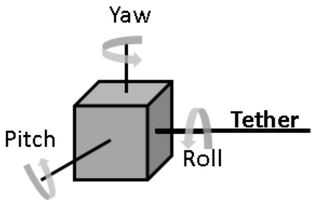

Figure 5: Pitch and Yaw are limited in their freedom by the tether, the roll initially is not

give a counteractive force. If this will occur depends on the material used for the tether and is considered unknown.

IV. SENSORS

For the satellite to measure the parameters described in section III both absolute and relative measurements are needed. Absolute position determination is necessary for the Kepler coordinates and can be found with observation from Earth, GPS and/or star tracking. Relative position and orientation sensors can be used to increase the accuracy of the absolute position determination or even give an absolute position with the measurements of several sensors combined. The relative sensors discussed are gyroscopes, accelerometers, hall sensors, sun sensors, horizon sensors, received signal strength indication (RSSI) from the inter satellite communication and the tension on the tether.

IV.1. Observation from Earth

Figure 6: Radio Telescope

Observing the required parameters from Earth would take a comparatively expensive procedures which only gives a value at the time of measurement, hence during a small interval of time and will not show slow changes such as variation in tether length due to heat. Tracking the satellite for a longer period of time would reduce or negate this problem, but would require a lot of resources.

IV.2. GPS

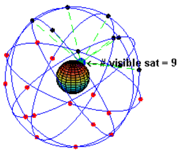

Figure 7: GPS constellation

The Global Positioning System (GPS) uses a constellation of satellites with finely tuned clocks which are used to determine the position of the observer, by the observer. This system works well on Earth and can be used in LEO and has already been demonstrated by, for instance, [3]. GPS can measure the position of the node, however it cannot determine its orientation. The advantage over observations from Earth are the continuous measurement and standalone capability. It has an accuracy of about 3 meter[13] at the moment for cubesats, however I expect this figure will improve within a short time due to continued research and development. According to [14] it takes about 9 hours to do the calculations needed to gain the actual position, in part because of the need to send a lot of data to Earth. This leads to consummation of a lot of power, commonly > 1 W though this is also improving.

IV.3. Star tracking

A different method to determine the position of the satellite is by tracking the stars. This can be done with a camera, a map of where the stars are and software to compare the two. Star tracking does not require an Earth link which is an advantage. It is also capable of continual measurement, as opposed to the measurement from Earth. It can determine both position and orientation of the node with an accuracy somewhere around the 7 arc seconds as for instance S3S star tracker[15]. The power consumption is about 1 W and therefore preferable over GPS. A star tracker always needs a clear line of view of the stars without reflections from other satellite parts or a direct view of the sun.

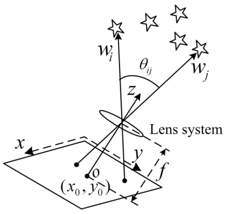

Figure 8: Observing the stars

IV.4. Gyroscopes

Gyroscopes can be used to determine the rotation of the node, with three orthogonal gyroscopes, one around each of the axes, every rotation can be measured. The off-the-shelf components can measure rotations of more then 1000 ° per second and are reasonably temperature stable. However they are prone to integration errors and therefore need compensation to determine the orientation angle.

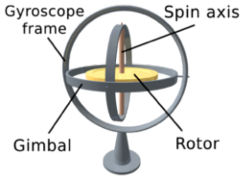

Figure 9: Impression of a gyroscope

IV.5. Accelerometers

Accelerometers are sensitive to both constant and variable accelerations such as the force of gravitation, part of the rotation of the node and linear accelerations. With three orthogonal sensors a 3D acceleration vector can be established. However no distinction can be made between the constant and variable accelerations. This means that certain maneuvers cannot be distinguished from each other. In addition, accelerometers are prone to integration errors when used to determine the position.

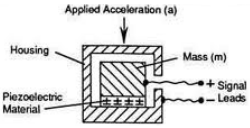

Figure 10: Impression of an accelerometer

IV.6. Hall sensors

Hall sensors, otherwise known as magneto sensors, can be used to determine the direction of the Earth magnetic field. In this way the orientation in two dimensions can be measured. However they are sensitive to all magnetic fields present including those produced by the transmission antennas which would have to be compensated.

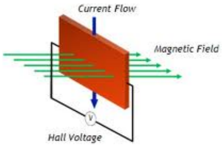

Figure 11: Measuring magnetic field

Sensor	Measures	Accuracy, longterm	Accuracy, short term	Power	Space	Other considerations
From earth	position, orientation	–	++	++	++	expensive
GPS	position	++	+	-	-	sending data to earth
Star Tracker	position, orientation	++	+	-	-	
Gyroscope	orientation	–	++	++	++	
Accelerometer	position	–	+/-	++	++	
Hall sensor	orientation	+/-	+/-	++	++	if possible to compensate for magnetic interference from antennas
Sun sensor	orientation	++	++	+	-	does not work in eclipse
Horizon sensor	orientation	+/-	+/-	+	-	does work in eclipse
RSSI	distance separating nodes	+	+	++	++	
Tension on tether	distance separating nodes	+/-	+/-	++	++	

Table 1: Comparison of the sensors for the TwenteSat operation

IV.7. Horizon sensors

Horizon sensors detect the orientation of the node with respect to Earth. It takes six sensors for an all round view and achieves accuracies smaller than 1 °. However the simple versions suitable for cubesats make no distinction as to which horizon is in view.

IV.8. Sun sensors

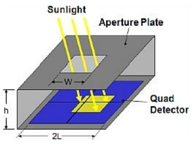

Figure 12: Measuring direction of Sun light

Sun sensors can detect where the sun is and therefore the orientation of the node.It takes six sensors, one on each side to sense in all directions. Solar panels can be used both as sensors and for power generation. They will be on most of the sides of the nodes to power them. Non power producing sun sensors generally have an accuracy of about 1 °when not behind the Earth.When the node is behind Earth the sensors give no relevant information. Solar panels have a much lower accuracy when not changing its angle, however as TwenteSat will rotate it can easily be determined when the solar panel has completed a full circle around the centre of mass of the satellite.

IV.9. RSSI

RSSI of the inter satellite communication measure the distance between the nodes[10]. An advantage is that almost no extra power consumption is needed for this measurement. The accuracy is dependent on the hardware implementation. However one of the common problems with this measurement principle, multipath fading, will not occur in the setup.

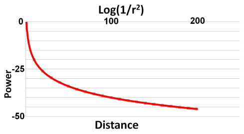

Figure 13: RF power vs distance

IV.10. Tether tension

The tension on the tether is related to its length and therefore the distance separating the nodes. However it would have to be characterized on Earth prior to launch and extra temperature measurement and compensation may be necessary.

Table 1 gives a comparison of the different strength and weaknesses of the sensors.

V. MEASUREMENT SETUPS

Two different measurement setups will be considered, namely a symmetrical setup and an a-symmetrical setup. The symmetrical setup will have the same sensors in both nodes whereas the a-symmetrical setup will not. In general both will consist of an absolute sensor and multiple relative sensors to improve the accuracy of the measurements.

As an absolute sensor the star tracker appears to be the best, provided it works with the rotation of the satellite system. Both sun sensing and RSSI require a minimal amount of extra hardware to implement and will therefore be used for additional sensing. The sun sensing will be done with the solar panels.

For the symmetrical setup the orbit will be measured solely by the star trackers, as shown in Figure 14. The distance between the nodes can easily be obtained from the positions as determined by the star tracker combined with the RSSI measurements. However the rotation plane orientation of the system with respect to Earth, the individual pitch, roll and yaw of the nodes and the current angle of a node in the rotating system are all measured at the same time by the star tracker and the sun sensor. An algorithm has to assign what part of the measured value belongs with

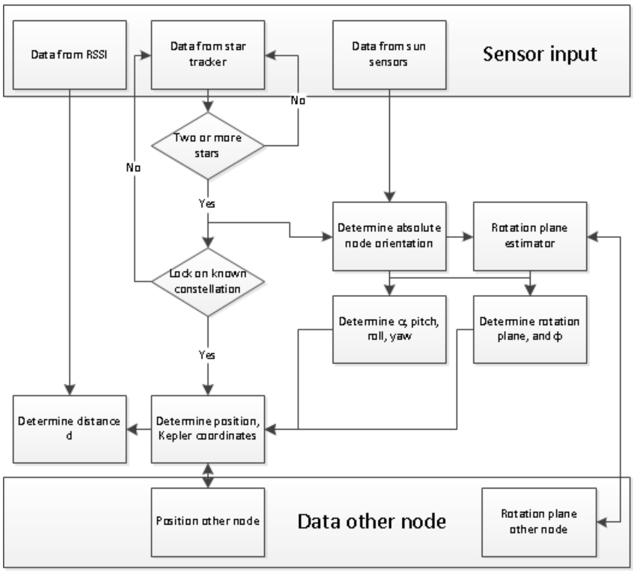

Figure 14: Flow chard global setup for symmetrical measurement

which parameter.

The main advantage of the symmetrical setup is the redundancy it provides. If one or a few sensor(s) were to fail, the position of the node can be deduced from the other, with the accuracy depending on what failed.

An a-symmetrical setup has the advantage of reduced mass, power and space used as compared to the symmetrical setup. However it cannot compare two independent results making it less accurate.

In this a-symmetrical setup only one node will keep all the sensors while the other only needs to measure its orientation. In order to do this which sufficient accuracy gyroscopes will be added to improve the measurements from the sun sensors. This gives the node more freedom in its budgets for the payload. However both nodes must have the same mass in order to stay balanced and fitted into the reference system described in section III.

With the knowledge of the position from the first node, the position of the second node can be calculated by using the direction of the tether and measuring the distance separating the nodes. The direction of the tether follows from the knowledge of the rotation plane, which has to be derived from the orientation of both nodes. One node will keep the setup of Figure 14 the other will only have gyroscopes and sun sensing as shown in Figure 15

The symmetrical setup is less complex and more redundant making it the preferred choice. However its implementation will be dependent on the mass, power and space budgeted. Alternatively an a-symmetrical setup will also work, though a lesser accuracy may be expected.

VI. CONCLUSIONS AND FURTHER RESEARCH

After identification of the necessary parameters to describe the orbit, the orientation of the rotation plane of the satellite with respect to Earth, the position of the individual nodes and their orientation with respect to the tether it was possible to give different system overviews of how to measure the relevant information to map data from the TwenteSat interferometer.

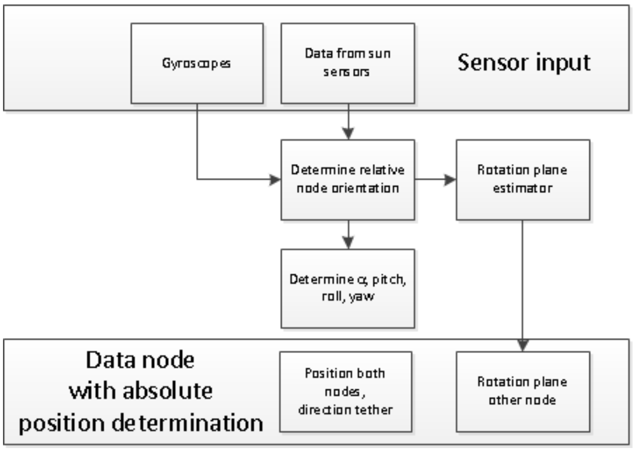

Figure 15: Flow chard global setup one node a-symmetrical measurement

The reference system can be used for any rotating twin-satellite in planetary orbit, including but not exclusively Earth. The proposed measurement setup can be applied in any rotating twin-satellite system and is not necessarily limited to symmetrical masses for the nodes or orbit around a planet, however a star map is needed to determine the position of the satellite.

With the proposed setup all relevant parameters can be measured making it possible to map the data from the interferometer. The components necessary to do this are a startracker, gyroscopes, intersatelite link for RSSI and solarpanels. The last two are already present for the LOAS mission. Further work is being done on system and hardware levels in order to implement the proposed system for TwenteSat within a year. This paper will be used as a stepping stone for the TwenteSat project to start with the hardware realisation of the satellite.

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