# ANALYSIS OF THE MEGHA-TROPIQUES TRAJECTORY. DETERMINATION OF RENDEZ-VOUS CONDITIONS WITH THE TERRA SATELLITE.

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***Abstract:*** *The main objective of this paper consists in analyzing to which extent an analytical propagation of the equations of motion is adapted or not to predict, accurately enough, the rendez-vous conditions between the two spacecrafts Megha-Tropiques and Terra. A rendez-vous configuration that occurred on 17th April 2012 is carefully analyzed, after determining the conditions in space and in time for which the observations between the two satellites can be overlapped.*

***Keywords:*** *Analytical propagation, Two-Line Elements, Megha-Tropiques and Terra satellites*

## 1. Introduction

The Megha-Tropiques (MT) mission was studied in France in the context of GEWEX (Global Energy and Water cycle Experiment). The first originality of Megha-Tropiques is to associate three radiometric instruments allowing to observe simultaneously three interrelated components of the atmospheric engine: water vapour, condensed water and radiative fluxes. The second is to privilege the sampling of the intertropical zone, accounting for the large time-space variability of the tropical phenomena.

The key of this mission is the repetitivity of the measurement in the tropical area. The trajectory was designed so as to take advantage on (i) the choice of the inclination of the orbit, (ii) the scanning capability of the instruments and (iii) the height of the orbit. As a consequence, the orbit ensures a repetitivity of more than 3.5 visibilities per day over each point of the zone located, in latitude, between 22°S and 22°N ; The repetitivity rises even up more than 5 visibilities per day around 13°S and 13°N: Megha-Tropiques is a LEO satellite, with a circular orbit, and a 20 degree-inclination. The choice of this inclination makes the spacecraft fly all points at variable local times, and, as we will see hereafter, from a given point a same local time occurs every 53 days.

In the framework of the calibration campaign for ScaRaB, one of the three MT radiometers, LMD proposed to compare the measurements provided by ScaRaB with those provided by CERES, a similar instrument aboard the Terra (NASA) satellite. So as to make the measurements be comparable, the two instruments had to observe the same scene, at the same time, and with similar geometrical conditions. In that purpose, it was decided to use the ability of the CERES instrument to change the scanning direction.

The first objective of this paper consists in analyzing to which extent an analytical approach based on a long period SGP4-like model is adapted or not to predict, accurately enough, the rendez-vous conditions between the two spacecrafts Megha-Tropiques and Terra. This model was implemented into the IXION s/w [1]. The IXION s/w was used to determine the conditions in space and in time for which the observations between the two satellites can be overlapped.

The second objective of the paper consists in comparing these overlapping conditions: the differences are analyzed and understood from a qualitative approach, in particular those appearing to be geographically correlated.

## 2. Scope of the study, and main properties of the two spacecraft trajectories

Terra and Megha-Tropiques are LEO (Low Earth Orbit) satellites devoted to the terrestrial environment survey.
Terra is a NASA satellite for the study of weather and for Earth survey, launched in 1999 and still operational. Its orbit is quasi circular, with a nominal semi-major axis of $a = 7077.8$ km (corresponding to an altitude of the order of $h = 700$ km), an inclination of $i = 98.2^\circ$ ; the orbit is Sun-synchronous with an equatorial (descending node) crossing time at 10:30 LMT (Local Mean Solar Time).
Megha-Tropiques is a joint Indian-French mission (ISRO for India, CNES for France) launched 12th October 2011. Its principal aim is the study of tropical weather and thus its orbital plane is near to the equatorial plane: its inclination reaches $i = 20^\circ$. Its orbit is quasi circular, with an altitude higher than the Terra one, with a nominal semi-major axis of $a = 7243.6$ km (corresponding to an altitude of the order of $h = 866$ km). The precession cycle w.r.t. the Sun, due to secular variations of the ascending node, is equal to 51.3 days, meaning that the satellite LMT at the equator is decreasing 28 minutes per day.

Both trajectories have been designed so as to get a cycle of recurrence (233 revolutions in 16 days for Terra, 97 revolutions in 7 days for MT), requiring strictly maintained orbits.

Several instruments are on board the two satellites. The rendez-vous conditions have been established in order to make two instruments on-board the satellites cover a common region flied more or less at the same time, and with the same angle of view: CERES aboard Terra, ScaRaB aboard MT, dedicated to the Earth radiation balance survey. These two similar instruments have more or less common requirements ; for both cases, the scan mode is perpendicular to the track (X-track mode) and the widths of swath are roughly equal (2330 km for Terra, 2216 km for MT). Figures 1 and 2 show the ground track of each satellite and the swath of each instrument (X-track mode).

The CERES instrument offers the possibility of varying the direction of the scan angle and thus of obtaining swaths that are not perpendicular to the track of the satellite (PAP mode, standing for Programming Azimuth Plane mode, Fig. 3). The ScaRaB instrument does not have this possibility (it is always in X-track mode). For the calibration/validation campaign of ScaRaB, NASA has accepted LMD research team request to change the direction of swaths of CERES.
In this way, when the tracks of the two satellites are very close one to the other, in space and in time, tilted-CERES and ScaRaB observe scenes with the same geometry (viewing zenith angle, solar zenith angle, relative azimuth between solar and satellite directions).

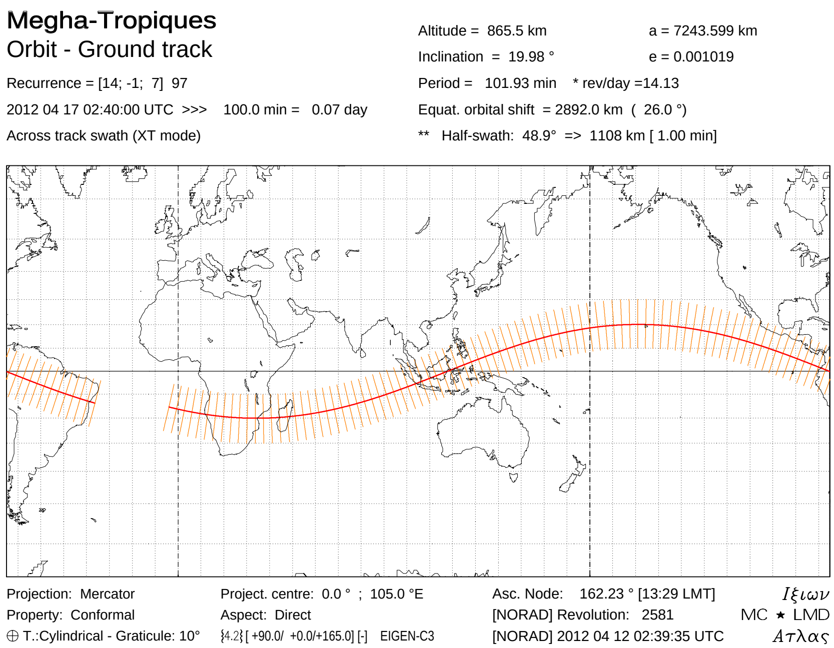


**Figure 1. Megha-Tropiques satellite(non sun-synchronous) typical ground track**

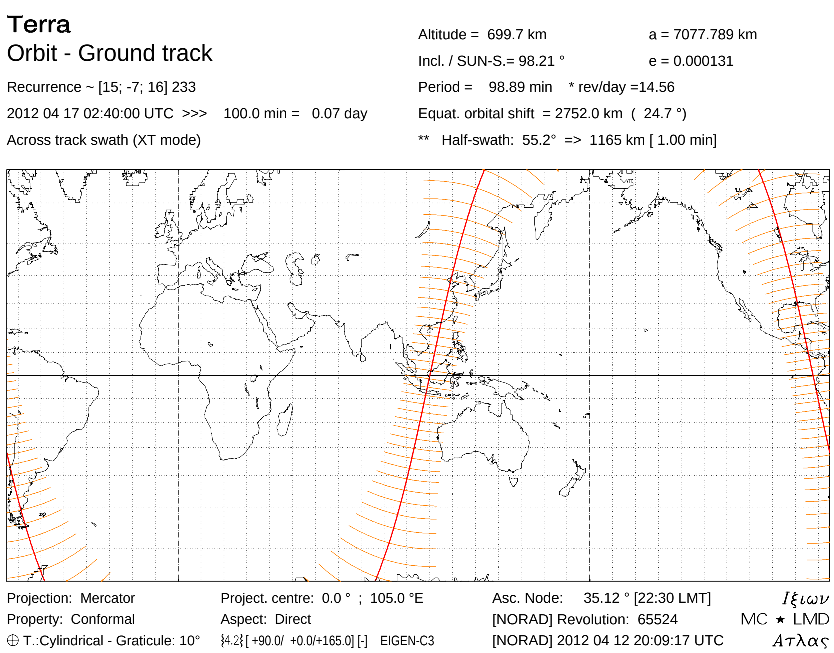


**Figure 2. Terra satellite (sun-synchronous) typical ground track**

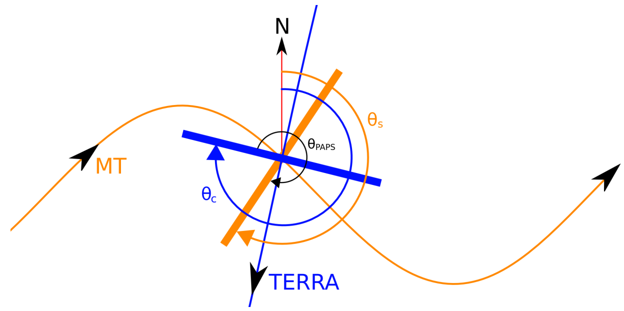


**Figure 3. Geometry of the Terra Programming Azimuth Plane mode**

Our task was then to predict:
– the instants where Earth regions would be seen by the two instruments simultaneously; the maximum allowed difference in time between the two trajectories flying a common point was fixed to 4 minutes, value established after estimating the typical temporal sampling of the physical phenomena variability to be observed;
– the value of the angle which allows to make CERES swaths (PAP mode) be parallel to those of ScaRaB.

The main difficulty, following NASA requests, was to provide values for one week, three days in advance (every Tuesday, we send the data for one week, from Friday to Friday), meaning that the maximum period between an initial state vector (through a TLE data set) and the time of prediction is about 10 days. As a consequence, it is worth investigating whether the accuracy of the TLE and the propagation model is precise enough to guarantee an accurate rendez-vous between the two satellites ten days in advance.

## 3. Determination of rendez-vous conditions between the Megha-Tropiques & Terra satellites

These rendez-vous conditions were determined using an analytical approach accounting only for the main secular perturbations that can significantly change the Earth-projected orbit.

### 3.1. Analytical propagation with the IXION s/w

The analytical model was implemented into a dedicated software called IXION, and it appears that only secular perturbations induced on the angular keplerian elements by the first zonal terms of the geopotential (up to $J_{10}$) are useful for the purpose we follow. Much more than a mere analytical approach, the main functionalities of the IXION s/w, very relevant for that kind of mission analysis, are the following:

- ⋆ the analytical modelling is initialized through TLE data sets ;
- ⋆ a large (among more than 100) choice of precise projections into an Earth-fixed frame, with arbitrary origin (even very close to those usually seen as singularities in "classical" projections such as the Mercator projection, Fig.4) and aspects (term which stands for, in cartography, the direction of projection) ;

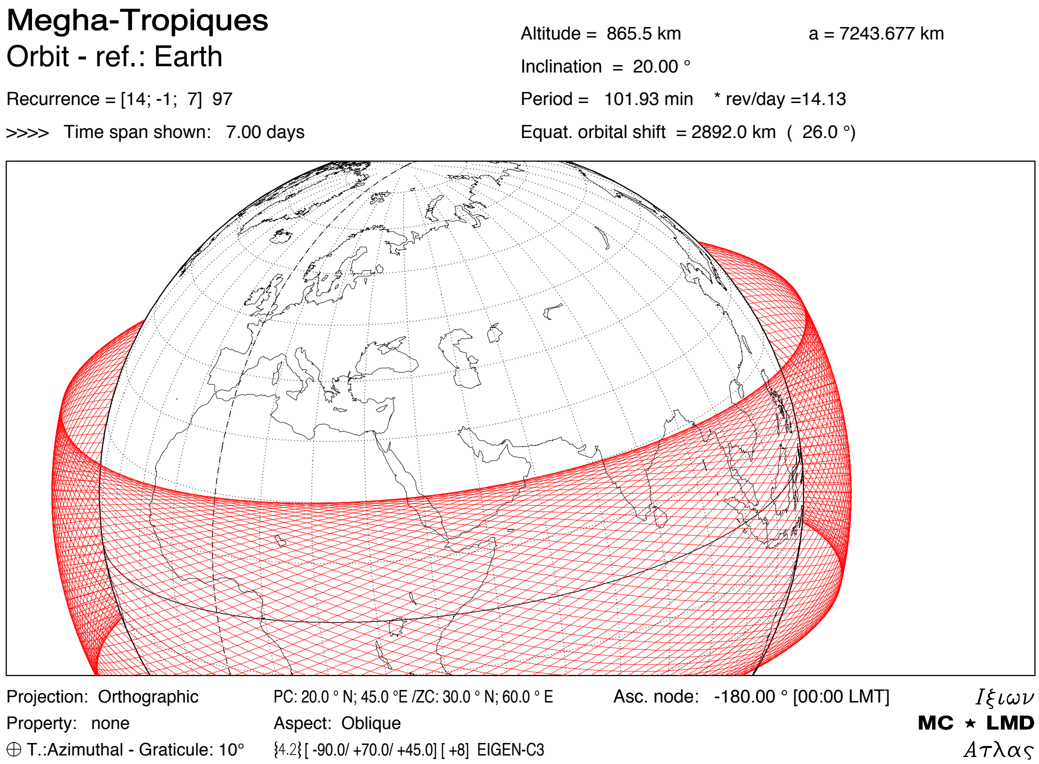


**Figure 4. Megha-Tropiques orbit over 7 days, from IXION s/w**

- ⋆ thanks to the projection capabilities, the change of attitude can be determined (in advance), which is very useful for the current purpose ;
- ⋆ information concerning LMT values are provided on each plot ;
- ⋆ synthetized results for space sampling are easily available, as well as eclipses ;
- ⋆ the overlapping conditions (such as Fig. 5, see hereafter), called ”rendez-vous”, can be easily determined, as well as radio-occultations between two satellites ;
- ⋆ the s/w can be used, to a certain extent, for real-time tracking ;
- ⋆ let’s say, additionally, that these functionalities are also available with Mars seen as the central body instead of the Earth.

### 3.2. Rendez-vous conditions over a precession cycle w.r.t. the Sun

Figure 5 shows the conditions of overlapping, during day-light, between MT and Terra, determined from the IXION s/w over a period of the ascending node of MT w.r.t. the Sun, covering therefore all the possible LMTs, for a given location. In a first step, common geographical coordinates for the two instrument swath are looked for ; in a second step only the overlapping conditions with a time interval difference shorter than 4 minutes are kept on.

It is worth remembering that due to the Sun-synchronous Terra orbit, the rendez-vous will always occur at the same solar local time (namely around 10:30, as already mentioned) ; mapping all the possible LMTs corresponds in fact to a search of all the possible longitudes of rendez-vous conditions.

On Fig. 5, a two-day regime can be noticed: a day with rendez-vous is followed by a day without any. Rendez-vous occur 4 or 5 times per day (we discuss only about those during day-light), at different longitudes ; they are separated in time by a revolution period of the satellites.

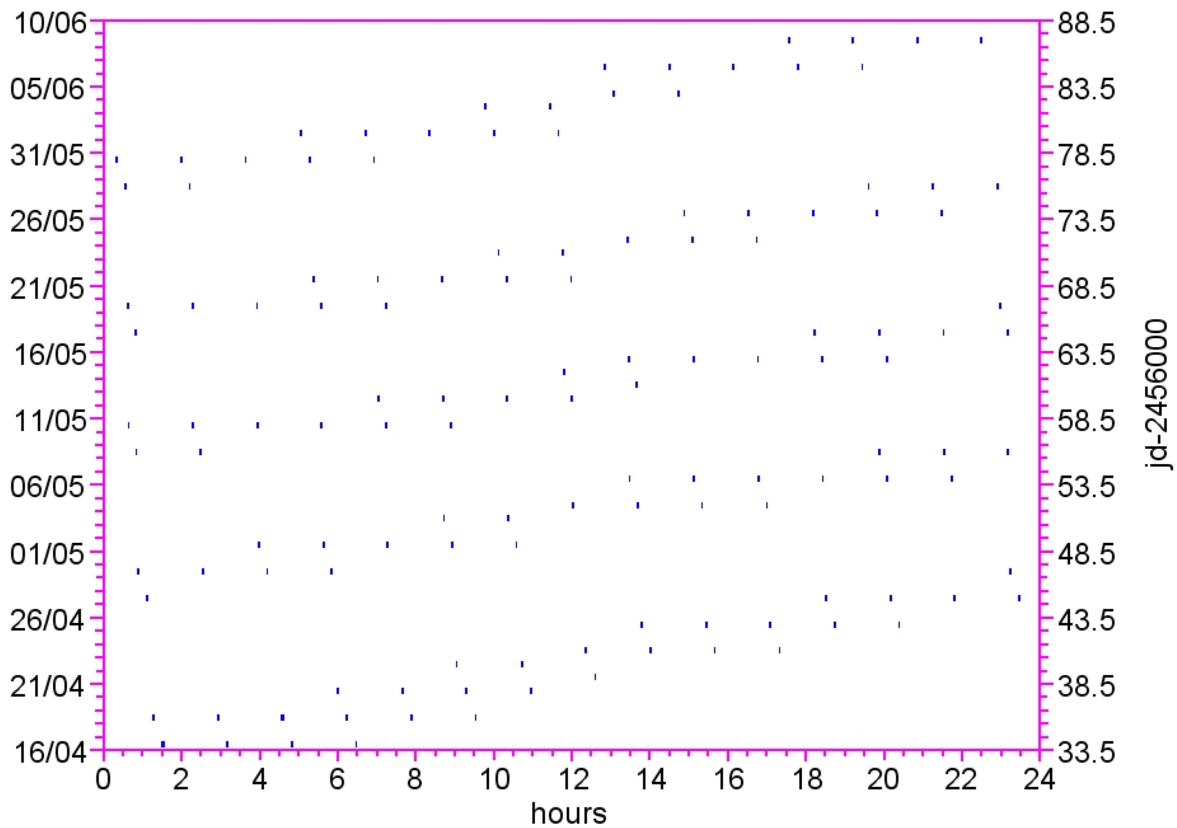


**Figure 5. Location of overlapping periods (day-light) between MT and Terra**

## 4. Analysis of the 17th April 2012 rendez-vous

Let's analyze the rendez-vous conditions on the 17th of April 2012. This date is chosen because it was one of the first time the two instruments aboard MT and Terra could work simultaneously.

### 4.1. Prediction for 17th April 2012

Figure 5 shows that 4 rendez-vous during day-light occurred at that time. In fact, a total of 9 rendez-vous occurred on 17th April 2012, 5 during night time (blue and green), 4 during day light (red and orange), as it can be seen in detail Fig. 6. This figure, obtained with the IXION s/w, shows areas where footprints can be superimposed with a difference in time (between the two satellites) shorter than 4 minutes.

As a result, LMD team provided to NASA, for each rendez-vous configuration, time series of (i) epochs, sampled every second, corresponding to a ground-space sampled of about 6 km, (ii) change of azimuth angle of the CERES instrument.

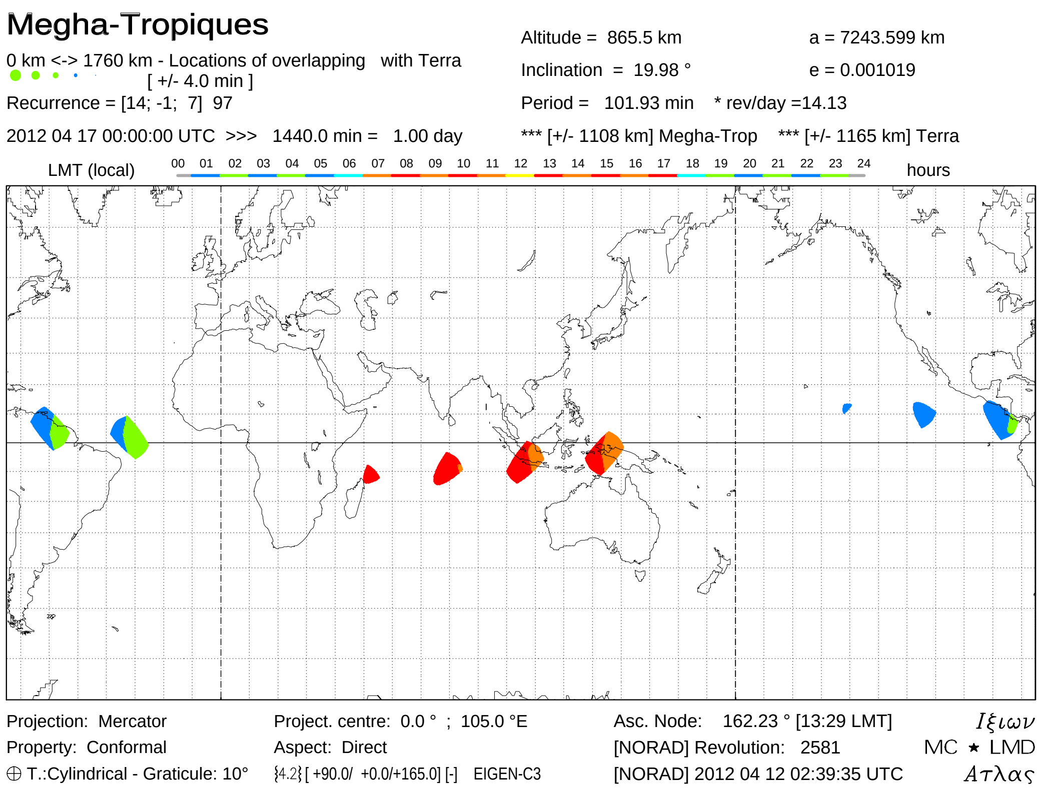


**Figure 6. Overlapping between MT and Terra, 17th April 2012 (IXION s/w)**

### 4.2. Results from real orbit

Figure 7 now shows a map of real results broadcast by the satellites themselves: real positions of the ScaraB pixels, and real positions of the CERES pixels (in PAP mode) were superimposed so as to get a view of the real ground-track of the two spacecrafts. Let's notice than, concerning the CERES instrument, it was possible to change the value of the azimuth angle in the only one rear direction. It is clear that, roughly speaking, the two swaths can be considered as parallel and simultaneous.

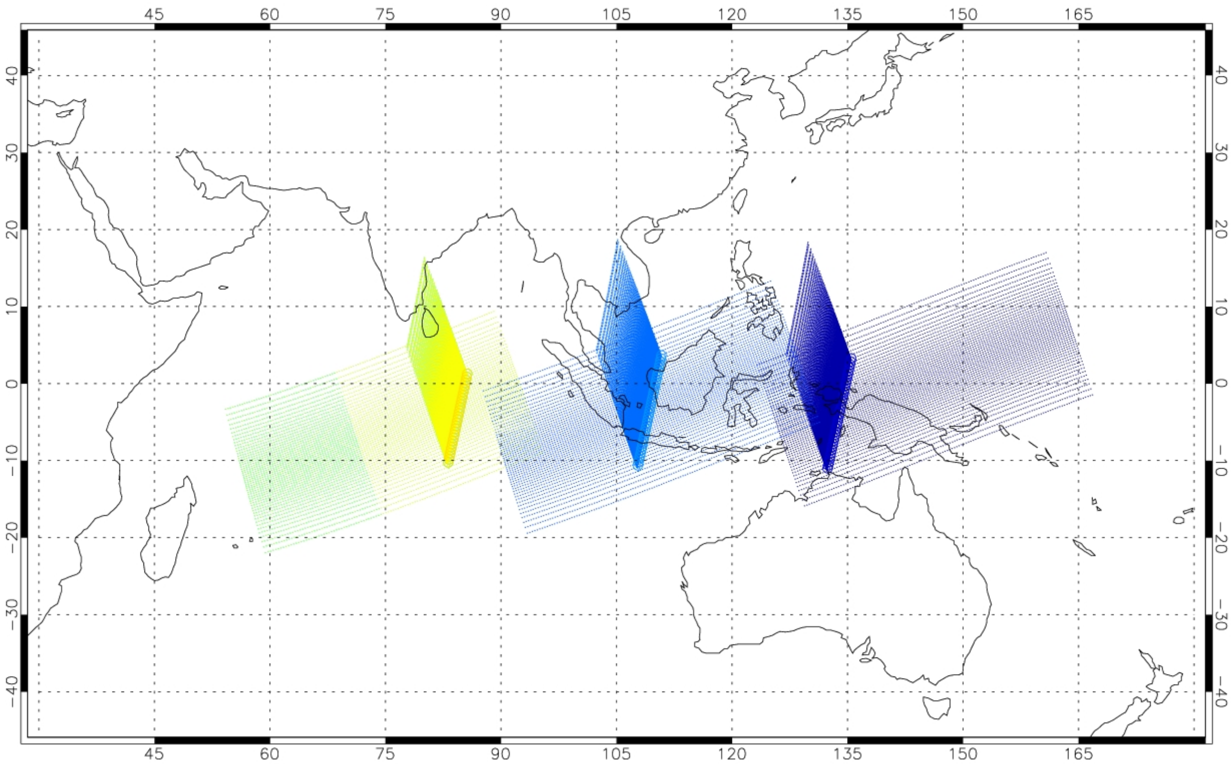


**Figure 7. Geometrical configuration of the 17th April 2012 rendez-vous (from real orbits)**

## 5. Impact of the TLE data set accuracy on the prediction quality

Let us consider only the second rendez-vous configuration of 17th April 2012, over the area of the Borneo island. As shown Fig. 8, the crossing point between the two trajectories is located 3.30°S 109.34°E. This plot were obtained on the basis of TLE data sets aged 1 day and 5 days, namely with a reference epoch prior to the 17th April, i.e. 16th April and 12th April respectively. In this section, we consider the trajectories from the 1-day aged TLE data set as the reference trajectories.

### 5.1. Geometrical description of the 17th April 2012 2nd rendez-vous

The distance between the two crossing points is of the order of 1.4 km: it can be considered that the rendez-vous location is well-defined, with a temporal error of the order of 0.2 s. The most interesting comments can then only be described when considering a time dependency of the differences.

To that purpose, Fig. 9 shows time series (same color chart as in Fig. 8) of the predicted longitude and latitude of the two spacecrafts. The time interval on the x-axis is of the order of 0.7 s between two label ticks ; the distance on the y-axis is of the order of 5.5 km. Let's describe the main characteristics of the differences:

- Difference on the geodetic latitude $\varphi$: the difference on the Megha-Tropiques satellite seems to be negligible, even after a blow-up of the plot ; the difference on Terra is higher, of the order of 1.6 km

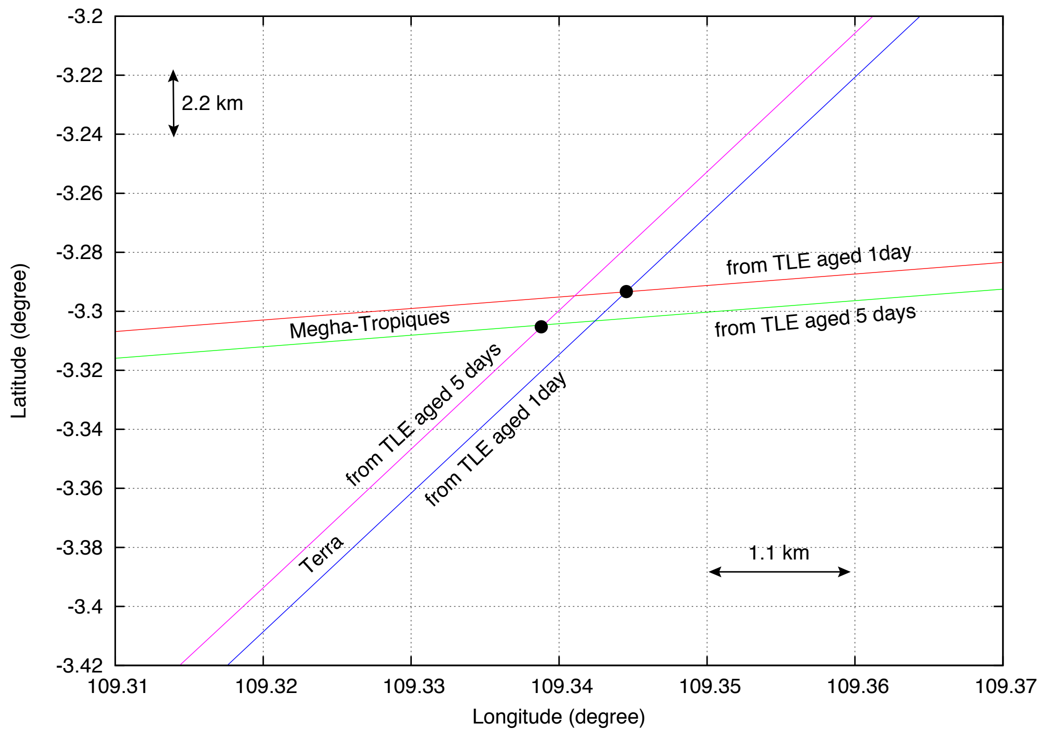


**Figure 8. Geometrical configuration of the 2nd 17th Apr. 2012 rendez-vous (from IXION)**

- Difference on the geodetic longitude $\lambda$: here, it is for the Terra satellite that the difference seems to be negligible ; the difference on MT is slightly higher, of the order of 3.8 km.
- Time dependency of the differences: for both satellites (mainly for MT), a part of the differences (mainly on the longitude) comes from a difference in time corresponding to the difference of epochs to fly a given longitude ; this induces on the Earth-projected orbit a change towards the West or the East. Here, it is roughly estimated that 0.3 km change seen on the 3.8 km for MT are due to the change of position on the orbit.

Megha-Tropiques is flying the crossing point at 03:13 UTC, and Terra at 03:10 UTC.

### 5.2. Dynamical interpretation

The two TLE data sets that we previously used, aged 1-day (16th Apr. 1.79427 UTC) and 5-day (12th Apr. at 2.65990 UTC) respectively have coherent metric orbital elements: the difference in the (mean) semi-major axis if of the order of 2 m, with a nominal value of 7243.596 km ; the (mean) eccentricity rises up to 1.025 $10^{-3}$, with a negligible difference of 6 $10^{-6}$ ; the (mean) inclination is 19.9777°, with a difference of the order of 0.001°. As a consequence, they will induce the same kind of secular effects on the angular orbital elements, namely the longitude of the ascending node $\Omega$ and the argument of latitude $\omega + v$ ; but, slight differences between these values evaluated at the two reference epochs (Table 1) will cause differences in (i) orbital angles (Table 2), and (ii) position

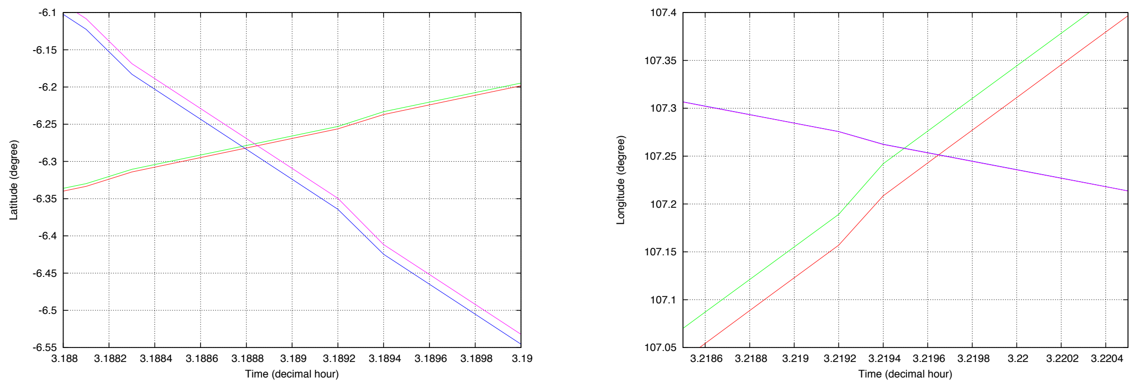


**Figure 9. Time series of geodetic latitude and longitude (from 2 TLE data sets)**

on the Earth surface large enough so as to be carefully determined, as we will see hereafter.

**Table 1. Secular effects induced on the Megha-Tropiques orbit, evaluated at two epochs**

| | Ref. epoch 12th Apr. 2.65990 h UTC | Ref. epoch 16th Apr. 1.79427 h UTC |
|---|---|---|
| $\dot{\Omega}$ | $-6.028860\ ^\circ/d$ | $-6.028833\ ^\circ/d$ |
| $\dot{\omega}$ | $10.961180\ ^\circ/d$ | $10.961033\ ^\circ/d$ |
| $\Delta\bar{n}$ | $5.290778\ ^\circ/d$ | $5.290688\ ^\circ/d$ |
| $\bar{n}_{pertub.}$ | $5085.846191\ ^\circ/d$ | $5085.849121\ ^\circ/d$ |

In Table 1, all digits are considered significant. It is worth noting that the secular effect on the perigee $\dot{\omega}$ and the variation of mean motion $\Delta\bar{n}$ are not directly used to derive the ground-track, but, have been accounted for the computation from the TLE data sets of the mean motion $\bar{n}_{pertub.}$. Table 2 then uses these values to propagate the orbital elements at the epoch of the 2nd rendez-vous of 17th April 2012, additionally to the values obtained from the TLE data sets.

**Table 2. Two sets of TLE, with related dynamical quantities**

| | $\Omega$ | $\omega + v$ |
|---|---|---|
| TLE (12th Apr.) | 42.8313° | 0.0431° |
| TLE (16th Apr.) | 18.9104° | 0.0502° |
| 17th Apr. $<$ 12th Apr. | 12.5471° | 347.2595° |
| 17th Apr. $<$ 16th Apr. | 12.5243° | 347.3197° |
| Diff. between two ref. | 0.0228° | −0.0602° |
| Equiv. distance | 2.533 km | −6.688 km |

Since the inclination can be considered as a constant value between the various epochs, distinguishing the differences induced on the ascending node $\Omega$ and the argument of latitude $\omega + v$ can be interpreted as a separation of the effects on the equatorial plane (linked to the variations on $\Omega$, and therefore to time bias due to the Earth rotation) and on the orbital plane (linked to the variation on $\omega + v$). It can be noticed that these angles correspond to the 3 well-known Eulerian angles (ascending node, inclination, argument of latitude).

Time-dependency of the longitude. The differences between the two determinations (Fig. 9, right) can be interpreted such as follows:

- the part due to $\Omega$, 2.533 km, has a direct impact on the longitude, when the orbit is projected on the Earth surface, because the two orbital planes have in this case two different orientations in space ;
- the part coming from the argument of latitude, $\omega + \nu$, $-6.688$ km(corresponding to 1 s error of time position), has the order of magnitude of the projection towards the equator ;
- the total difference is estimated as $2.533 - 6.688 \cos i = -3.752$ km, which is coherent with (Fig. 9, right).

Time-dependency of the latitude. The difference can be easily interpreted with the well-known formula $\sin\varphi = \sin i \sin(\omega + \nu)$, and this explaining why the latitude estimated from the ”older” TLE data set is lower (absolute value) than the ”younger” one.

Interpretation on the trajectory projected to the Earth. This part has now nothing to say with the satellites being in advance or not: only the geometrical configuration is at stake. The difference between the two ground-tracks of MT is of the order of 1 km.

The final comment concerns the level of accuracy of the TLE data sets themselves. It is clear that the difference shown on the two estimated values for $\Omega$ at the two reference epochs comes from the initial value of $\Omega$ than are not fully compatible five days or one day prior to the delivery of the rendez-vous conditions: as expected, the value of initial $\Omega$ seems to be refreshed regularly.
The change shown on the argument of latitude does not come from a change of semi-major axis, or inclination in the TLE data sets (even if the change of the secular variations are 1 order of magnitude higher than for $\dot{\Omega}$). Once again, the main origin of the predicted value for the argument of latitude comes from a refreshment of the initial values at TLE epochs.

## 6. Conclusion

Based on the examples that we examined here, it seems that determining rendez-vous conditions 10 days prior to the event leads to results that are fully compatible with the requirements of the experiment. A slight difference in time and in location can be observed between the results obtained with TLE data sets referenced at various epochs (typically: 1 day, 5 days), but both can be used.

*The authors would like to thank Z. Peter Szewczyk, NASA, for helpful discussions and for establishing change conditions in the PAP mode of the CERES instrument.*

## 7. References

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