OPERATIONAL CONCEPTS REFINEMENT FOR THE ORBIT DETERMINATION OF METEOSAT THIRD GENERATION

Pessina S.[(1)], **De Juana J. M.**[(1)], **Fernandez J.**[(2)], **Lazaro D.**[(3)], **Righetti P.**[(1)]
[(1)] *EUMETSAT, Eumetsat Allee 1, Darmstadt, D-64295 Germany +49 6151 807 7*
[(2)] *GMV at EUMETSAT,* [(3)] *Space Operation Consulting at EUMETSAT, addresses as above*
Stefano.Pessina@eumetsat.int, Jose.DeJuana@eumetsat.int,
jfernandez@gmv.es, David.Lazaro@eumetsat.int, Pierluigi.Righetti@eumetsat.int,

Abstract: *The Meteosat Third Generation (MTG) is the next series of the European operational meteorological satellites of EUMETSAT in geostationary orbit. Six satellites will be carrying the imaging and sounding payloads, the first of them planned to be launched at the end of 2017. To support the on-board operations, the Flight Dynamics System has to determine the orbit and to update its prediction regularly. For MTG, this task is dependent on the availability of Image Navigation and Registration data: in routine operations, INR data are available and they are used with single-station ranging to perform the Orbit Determination (OD), while to initialise the INR process and in case of orbit manoeuvres, the OD is based on traditional dual-stations ranging. Different level of performances can be achieved in the orbit determination process, according to the geographical location of the ranging stations, the interval between measurements, the frequency of stations swaps and the measurements' error. This paper will describe the methods adopted within MTG programme, for a trade-off and refinement of the operational concepts and requirements. To perform this study, the adopted technique is the covariance analysis: this allows identifying the error sources, to estimate their contribution to the orbital accuracy, and to address possible strategies to reduce determination error, simulating the full orbit determination process in a representative way.*

Keywords: *Mission Analysis, Orbit Determination, Dual-Ranging, Covariance Analysis, SRIF*

1. EUMETSAT and Meteosat Third Generation (MTG)

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) is an international organisation, founded in 1986, whose main purpose is to deliver weather and climate-related satellite data, images and products, 24 hours a day, 365 days a year (see [1]). These information are supplied to the National Meteorological Services of the organisation's Member and Cooperating States in Europe, as well as other users world-wide.
The Meteosat Third Generation (MTG) System of EUMETSAT is the next series of the European operational meteorological satellites in geostationary orbit (see [2] and [3]). It will provide continuous high spatial, spectral and temporal resolution observations and geophysical parameters of the Earth/Atmosphere System, from direct measurements of its emitted and reflected radiation from geostationary orbit.
The first European imaging meteorological satellite was launched in 1977, with 3 spectral channels and a mass of about 800 kg. The imager of the currently flying Meteosat Second Generation (MSG) has 12 spectral channels and it is a 2-tonne class spacecraft. The Meteosat Third Generation Imager (MTG-I) will be a 3.6-tonne satellite with 16 channels. Not present in previous generations, one of the key innovations in the new programme will be the MTG

Sounder (MTG-S), based on the same platform but carrying different instruments. It will consent also to analyse the atmosphere layer-by-layer and perform far more detailed chemical composition studies. MTG-I, will fly the Flexible Combined Imager (FCI) and the Lightning Imager (LI), while MTG-S, will include an interferometer, the Infra-Red Sounder (IRS) and the GMES Sentinel-4 instrument, the Ultraviolet Visible Near-infrared (UVN) spectrometer.

Unlike all the previous spin-stabilised Meteosat, MTG will be based on three-axes stabilised platforms, to achieve compliance with more demanding user requirements (on spatial resolution, repeat cycle, signal to noise ratio) and to conduct soundings from geostationary orbit. In the routine operations phase, the attitude will be controlled by reaction wheels based on star trackers measurements.

The mission will comprise 6 satellites: 4 imaging (MTG-I) and 2 sounding (MTG-S) satellites.

The full operational capability foresees one Imager operating the “Full Disk” service and one Sounder in the same longitude slot (nominally 0°, with ±0.1° width) with another Imager at 9.5° E, for the “Rapid Scanning” service; a 4^{th} satellite (Imager or Sounder) may be simultaneously launched and deployed at 3.4° W longitude, for the commissioning phase; the system has the capability to co-locate up to 4 satellites in the same longitude slot. The nominal inclination is less than 1° while the longitude range is 10°W to 10°E, with possibility of degraded mission for high inclination (2.5°) or in an extended range (50°W to 70°E).

The programme is currently in Phase-B, during the Preliminary Design Review; the first launch is scheduled at the end of 2017. The MTG system should guarantee access to space-acquired meteorological data until at least 2039, with flexibility of in orbit deployment in view of in orbit status, to maximise the duration of the operational service between MSG and MTG.

2. Flight Dynamics System and Orbit Determination for MTG

MTG has stringent accuracy requirements for the instrument data navigation and rectification (see [4], [5], [6]). For the Imager, the most stringent requirement is the absolute geolocation knowledge error needed for the Flexible Combine Imager. For the Sounder, the requirements for geolocation are more relaxed, however with more demanding requirements for the pointing stability. Most of the geometric requirements express the needs of image navigation: the main task is to estimate a-posteriori the position and attitude of the spacecraft from available measurements, to reconstruct the best possible knowledge of the localization of each sample for subsequent image re-sampling. To obtain an accurate orbit and attitude determination, the best architecture needs to make the most efficient use of on-board processing (i.e. attitude determination), ground measurements (i.e. ranging) and ground processing in order to obtain the best localization knowledge. This necessitates an Instrument Data Processing Facility (IDPF) for combined orbit/attitude determination, matching known landmarks to the payload data and using star-trackers attitude information.

The MTG satellites will be operated within a dedicated longitude and latitude slot (±0.1° and ±0.5° respectively), due to the frequency allocation constraints on the geostationary ring, as well as the cost benefits in reducing the number of ground stations. The angular separation between co-located satellites allows simultaneous tracking of two satellites using a single S-Band station (as studied in [7]). On the other hand, the co-location requirement creates additional operational constraints on the orbit accuracy (to always maintain a minimum safety separation between the collocated satellites) together with more operational complexity, because of the increasing number of station keeping manoeuvres (see [8]).

The operational concept for MTG foresees the IDPF, to fulfil the requirements for instrument data navigation and rectification; for this purpose, the IDPF processes payload and star-tracks data, using an estimation filter that needs to be initialised with an accurate orbit, and then will operate autonomously.
The IDPF will be separated from the Flight Dynamics Subsystem (FDS), which will be instead part of the Mission Operations Facility (MOF), together with the Mission Control Subsystem, the Mission planning Subsystem and the other MOF tools (for operations preparation, analysis, reporting and automation). The FDS has to determine the orbit and to update its prediction regularly, to support the on-board orbit propagator, the pointing of on-ground antennas and the orbit control of single or co-located satellites.
For MTG, this task is dependent on the availability of Image Navigation and Registration (INR) data from IDPF, as time-stamped orbital state vectors, as shown in Fig.1:

- INR data not available: the orbit determination and prediction are based on ranging measurements from 2 different Telemetry, Tracking and Command (TTC) S-band ground-stations, with frequent swaps (down to 3 hours). This is done to re-initialise IDPF, during payload off periods, safe mode and in the spacecraft commissioning phase.
- INR data available: this is the nominal routine scenario, with orbit determination and predictions based INR data, together with ranging from a single station. A second ranging station is used as cold back-up, with less frequent swaps (in the order of days) for maintenance and station bias calibration.

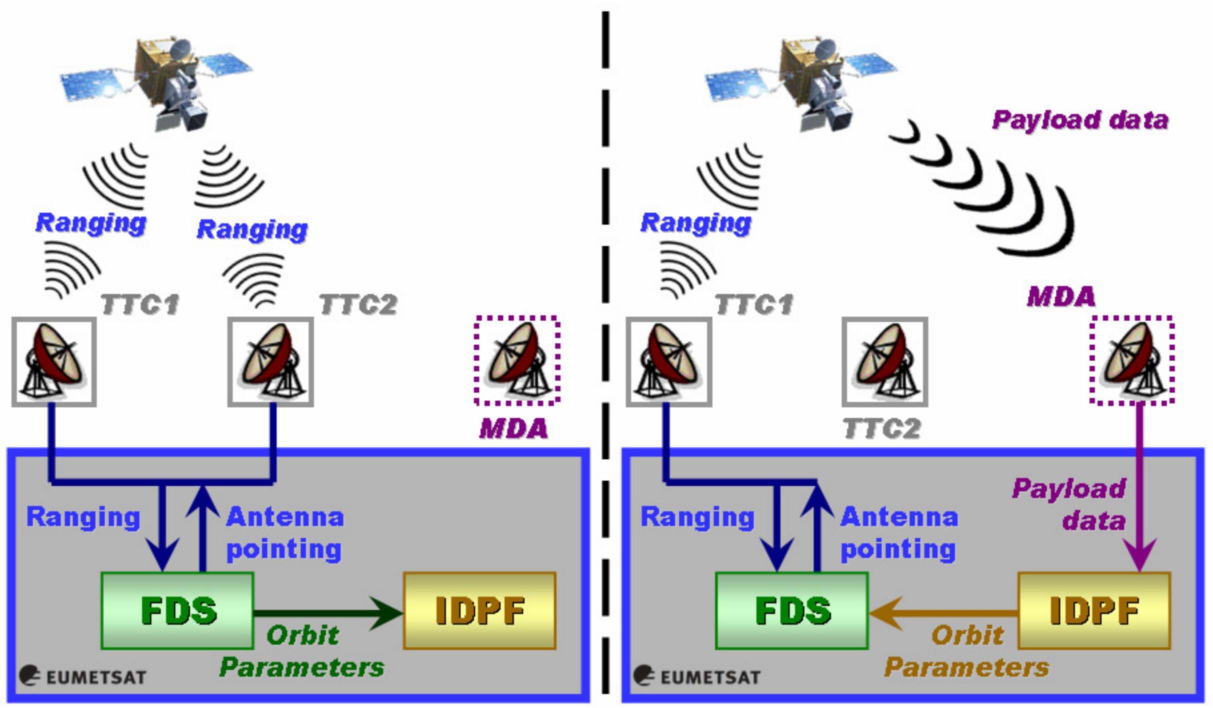

Figure 1: MTG Orbit Determination schemes. Right side: dual-stations ranging (INR data not available); Left side: single-station ranging and INR data (Routine Operations). MTG-I artist impression (credit ESA)

3. Orbit Determination requirements for MTG

In case of dual-stations ranging, the current operations baseline (see [4]) requires a near real-time orbit determination accuracy from the Flight Dynamics System better than 1500m/500m/50m in the along-track/cross-track/radial directions, at 3-sigma confidence level, with the ranging stations located on the territory of EUMETSAT member/cooperating states (see Fig.2, indicating in green the member and in blue the cooperating states; the figure shows also 13° elevation limit for the nominal longitude range and both 13° and 5° elevation limit for the extended longitude range). The necessary duration of the tracking arc will be estimated in the course of this paper.

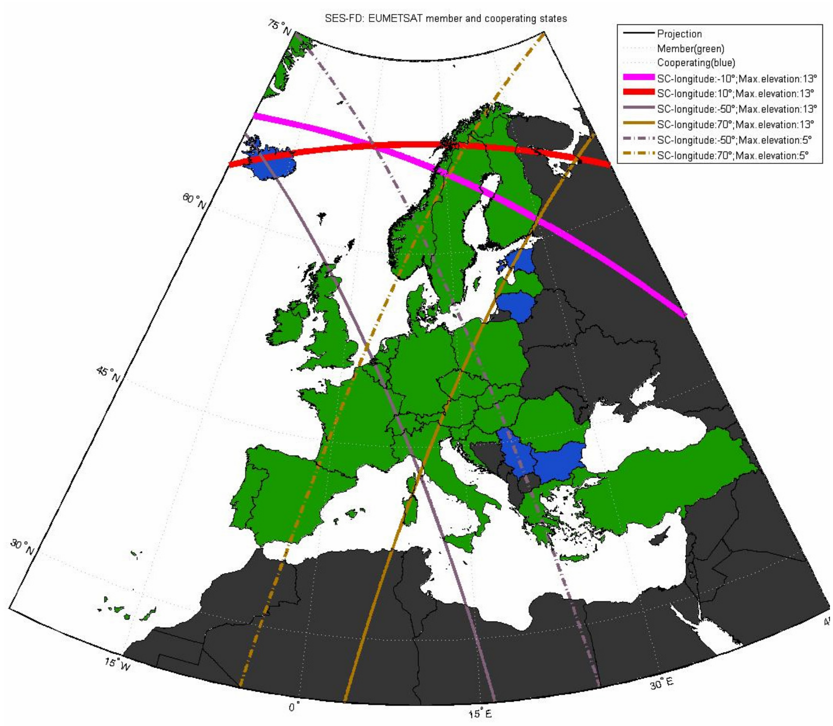

Figure 2: EUMETSAT member/cooperating states

For the case of INR with single-station ranging, the requirements are the same, with the exception of the radial accuracy. It is possible to achieve high accuracy of the orbit determination process based on dual-ranging techniques, properly selecting the ground stations' geographical location (i.e. increasing their relative distance), the frequency of the measurements and swaps between stations, or reducing the uncertainty in the process, such as measurement noise. These have an opposite impact on the cost, maintenance and operational effort for the selected design.

This paper will focus on the MTG orbit-determination based on dual-ranging, when INR data are not available: it will illustrate the methods adopted for a trade-off and refinement of the operational concepts in handling ranging stations swaps and measurement scheduling, as well as for definition of requirements for the geographical location of the stations.

4. Mission Analysis tool for orbit determination studies

For the purpose of the analysis, it is necessary to use mission analysis tools that simulate the orbit determination process in a representative way, giving a reliable statistical content in the results. TRAMOS (TRacking Analysis with Monte-carlo Simulations) is proprietary software, procured by EUMETSAT. The simulation concept foresees the use of high accuracy models for orbit propagation and measurements generation: the supported measurements include ranging, Doppler, antenna angles, landmarks and PVT data (Position-Velocity-Time). For MTG, phase-A studies identified an adequate design of Flight Dynamics Subsystem based on ranging only, which will be therefore the only measurement type considered in this analysis. The solution for the trajectory determination is implemented by means of covariance analysis with a square-root information filter (SRIF, see [9]); the orbit determination performances are obtained in time intervals, during which a batch of measurements is processed altogether, to obtain an update in the knowledge of the system state. The use of SRIF allows obtaining an estimated deviation in the state vector at the beginning of the mapping time interval. This is done by merging the a-priori accuracy information with those provided by the associated dynamics and the measurements in a mapping time interval. Then, the augmented state and the covariance matrix are propagated to the next mapping time. This approach allows including in the estimation process not only the modelling of the dynamic variables, as defined by their equations, but also the effect of exponentially correlated random variables and considered biases.

The measurement-generation and covariance-analysis modules allow for simulating various uncertainties of the orbit determination process, such as local terrain displacement of stations, effects of the troposphere and ionosphere (including periodic variations), measurements noise, ground stations and spacecraft transponder delays, uncertainties in the solar radiation pressure or geopotential coefficients. The tool allows generation of a reference trajectory, simulating the spacecraft "true" orbit. After definition of the uncertainty in the a-priori knowledge of the orbit on-ground, one can select the geographical location of the 2 ranging stations, the scheduling of the ranging measurements and of the stations swaps, together with other source of uncertainty in the process (such as noise in the measurements, error due to ionospheric and troposheric corrections). The output of the tool gives the evolution of the 1-sigma position and velocity accuracy as function of time. An example of the output of the Covariance Analysis module for position is shown in Fig.3, giving the position accuracy in semi-logarithmic scale, as function of time, for a test case based on dual-ranging (in the specific case: TTC stations are located in Canary Islands and Athens, with stations swap every 3 hours, ranging measurements every 20 min, tracking arc 24 hours). A successive arc of pure propagation is used, starting from the acquired orbit determination accuracy, to evaluate the final accuracy at the end of tracking, also considering the typical oscillating uncertainty in along-track, cross-track and radial direction (due to errors in determination of the eccentricity). For improved statistical results, the orbit determination can also be implemented in Monte Carlo sense, not be employed for this analysis.

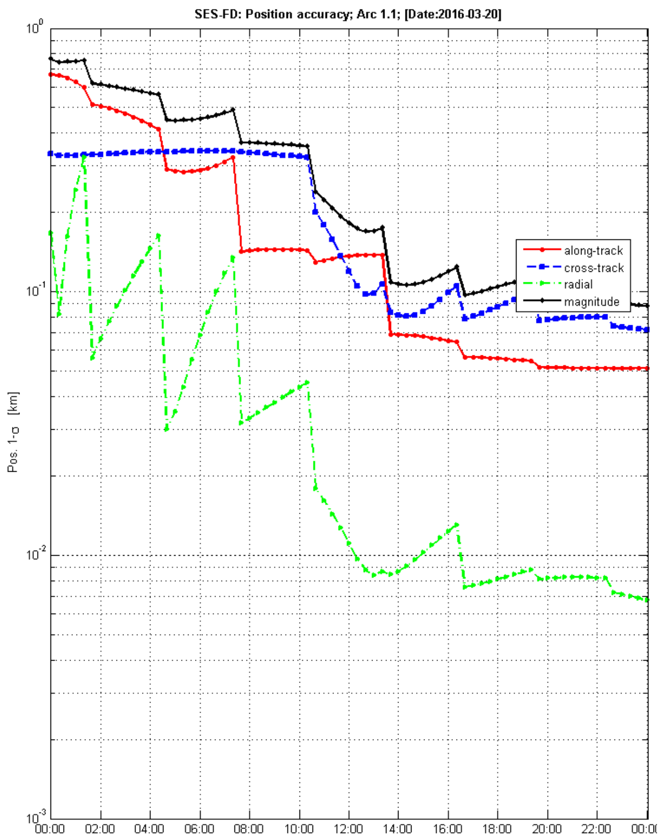

Figure 3: Covariance Analysis output

5. Ranging measurements error budget

The next step in the analysis is to provide representative figures for the error contributors to the measurement involved in the orbit determination process. Regarding ranging, the error budget is based on operational experience on the other EUMETSAT geostationary satellites, state of the art accuracy of ground models, together with updates from the latest figures in the phase of MTG ground segment design and link budget considerations. The ranging measurements error budget is summarized in Tab.1. The budget is divided in high frequency errors (that could be represented as white noise), periodic variations (daily) and long term variations (impacting the determination process as biases). For the dual ranging based orbit determination, a preliminary sensitivity analysis was run on the various errors contributors, using a single geometry with TTC stations in Usingen (Germany) and Fucino (Italy). The tracking schedule is assumed to have ranging measurements every 180 min, stations swaps every 24 hours, with 4 days determination arc; the reference case, assuming all errors contributors from the budget, had a final accuracy of 134m, 154m, 19m in along-track/cross-track/radial. The simulation has been repeated, de-activating for each run one component off the error sources. The noise on ranging measurements and on-board transponder were not considered, as the MTG system had clear and fixed requirements for this. No evident improvements in the accuracy of the solution were not observed when: using low solar activity model for ionosphere delay (instead of high), removing the ground-station bias on 1 station, removing bias on station coordinates. When removing the bias on troposheric delay for 1 station, the results changed more significantly, to 115m along-track; increasing the period of daily term for ionospheric delay, this made the results slightly worse (169m cross-track, 20m radial); without bias on the ionospheric delay for 1 station, the accuracy dropped to 154m cross-track , 19m radial. With no daily ionospheric delay error for GroundStation-1, the results changed to 120m cross-track, 14m radial. Removing all errors on ionospheric delay for both stations, the results changed to 99m along-track, 30m cross-track, 5m radial. The results of the sensitivity analysis showed that largest contributor to the determination performances is due to daily variations, specifically the ionospheric delay. A well-established a-priori model, such as the International Reference Ionosphere model (IRI, see [10]) could have errors contributors of 2.32 m in ranging (1-sigma) for the daily variation and 0.58 m (1-sigma) as long term bias.

Table 1: Ranging Errors

Error description	1σ[m]
High frequency errors	
Gr. Station noise	1.38
Transponder noise	1.50
Clock	~0
Daily variation errors	
Clock	~0
Solid tides	~0
Ionosphere delay	2.32
Troposphere delay	0.35
Gr. Station delay	0.53
Transponder delay	~0
Long term variation	
Clock	~0
Solid tides	~0
Ionosphere delay	0.58
Troposphere delay	1.0
Station	2.0
Gr. Station delay	1
Transponder delay	1

Due to the stringent orbit determination accuracy requirements, the performances obtained when assuming such errors (specially the daily variation) cannot be compensated for, thus resulting in not adequate performances.

Instead of these models, the ionospheric delay can be more accurately computed based on Total Electron Content (TEC) maps, from actual GPS measurements (see [11]).

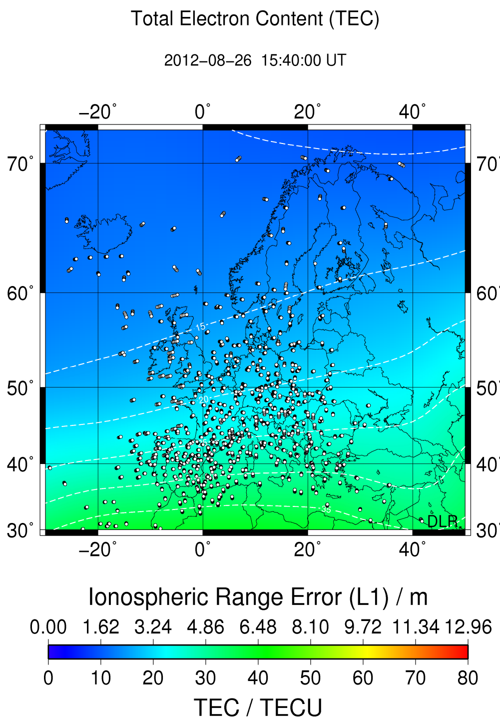

Figure 4: TEC map from SWACI

These have with ranging error contributors negligible for long term biases, and in the order of 0.28m 1-sigma for the daily variations (obtained from the worst case accuracy in determining the ionospheric delay, in case of high solar activity, from GPS L1 to S-band frequency). These TEC measurements are available for various service providers and with adequate time resolutions (as an example, see Fig.4, from [12]). The use of TEC maps would require the addition of an external interface to data provider for the routine operations, but, indeed, it allows to fulfil the orbit determination requirements with less demanding constraints on the ground segment (such as the required geographical separation of the ranging stations). Triggered from this analysis, it was agreed to add specific requirements for the Mission Operations Facility, to cope with TEC table based ionospheric correction. Therefore, for all subsequent analyses, the ranging error contributors are assumed as from Tab.1, but with ionospheric delays from the use of TEC maps.

6. Dual-Stations OD for variable tracking arc, stations swap, ranging schedule

One target of the MTG ground segment design was to clearly identify requirements for the geographical location of the ranging stations, to be included in the requirements documentation for the related procurement. Some simplified analyses using a longer observations arc were run in the past, drafting a stations separation requirement of 10° in longitude, as sufficient to fulfil the orbit determination requirements (indicated in Section 3). The purpose of this analysis is to verify this condition or to better characterise it, improving the statistical content of the simulations to support the conclusions. The analysis involves all possible 232 combinations of baselines for a wide range of existing ground stations in Europe (see Fig.5, equi-rectangular

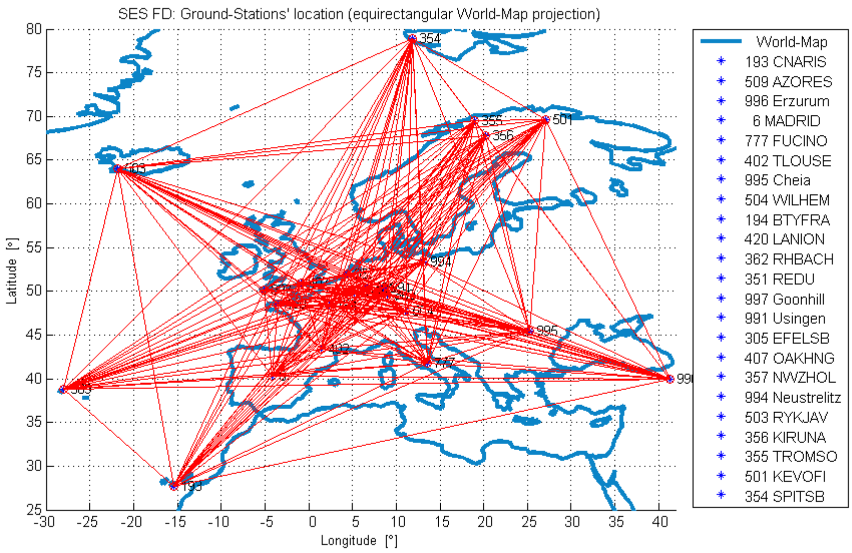

Figure 5: Baselines for initial assessment on dual-ranging OD

longitude/latitude map); each of these baselines is analysed with the Covariance module of TRAMOS, considering all possible combination of different station's swap schedule and ranging interval. The considered stations' swap scheduling ΔT is every 12, 6 and 3 hours, with the first swap occurring at after half ΔT inside the tracking arc (as an example, for 24 hours tracking arc, considering ΔT = 12 hours, the stations swap occurs after 6 hours of simulation). The considered intervals between consecutive ranging measurements are 180, 60 and 20 minutes, either if they are from the same station or different stations. Every simulation run is repeated for 3 different tracking arcs of 1, 2 and 3 days duration.
The uncertainty in the measurements has been specified in Section 5; furthermore, the initial accuracy/dispersion in the knowledge of the orbit state is assumed to be (along-track/cross-track/radial, as 1-sigma): 666.67 / 333.33/ 166.67 m in position, and 10 /25 /50 mm/s in velocity. This is representative of a case for INR (re-) initialization, due to a spacecraft or instrument safe-mode causing a gap of 3 days in orbit knowledge; in fact, this is compatible with the MTG orbit propagation requirements over 72 hours. This set of simulations considers the spacecraft at 10° longitude West only. For each geometry, the output of each simulation is the achieved Orbit Determination accuracy in the specific tracking arc, for each with given ranging schedule (swap and time between measurements); these can be represented as function of the geometric properties of the baselines, such as longitude and latitude separation, and compared back with the requirement. An example for the radial 1-sigma accuracy is given in Fig.6, together with corresponding OD requirements (horizontal dash-dotted lines): radial position requirement 50m 3σ => 16.67m 1σ. As it can be seen from the plot, looking at the envelop of the results, it is possible to identify "sufficient" conditions for the baselines, in order to fulfil the requirements; in this specific case, they would be: longitude separation > 23.9° or latitude separation > 5.9° (or great circle distance > 17.5°), indicated by the pointing arrows. It is also possible to indicate the percent of the baselines compliant with the requirement (in the specific case 58.6%). The same exercise of identifying sufficient condition has been repeated for all simulations involving different tracking arc duration, stations' swaps scheme or interval between consecutive ranging. As observed in the output, the orbit determination performances are degraded when one of the stations sees the spacecraft at very low elevation angle.

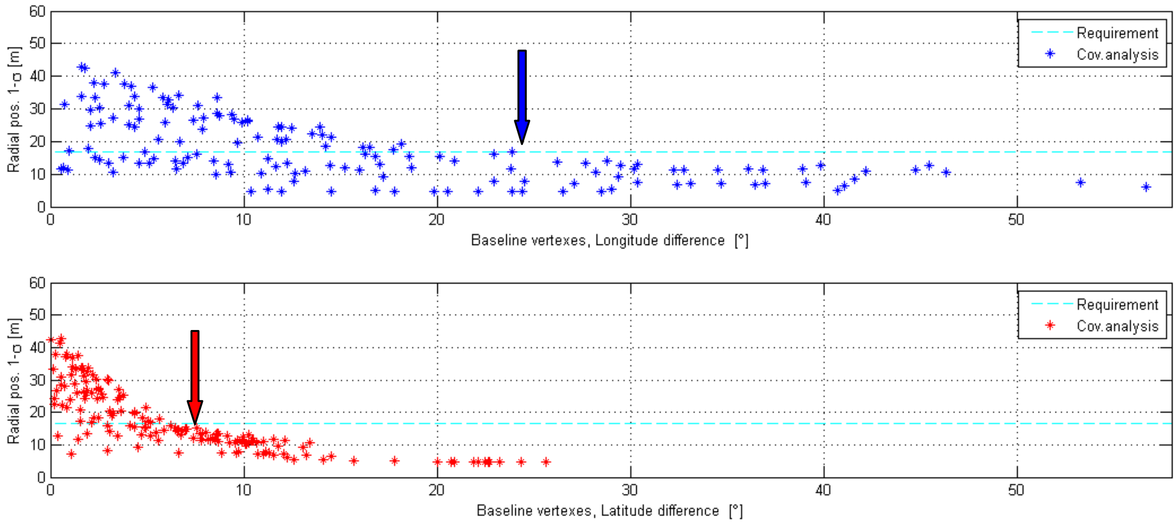

Figure 6: S/C at 10°WEST, OD results for Radial position accuracy, function of baselines' longitude(top) and latitude(bottom) separation in [°], highlight on sufficient conditions.

Therefore a filter on 13° elevation is used during post-processing (see red/magenta north limit in Fig.2). The cross-track and along-track OD requirements resulted to be in all cases less demanding than the radial, from the point of view of the required geometric separation between stations. Therefore, the results are summarised in Tab.2 for the radial OD accuracy only.

Table 2: Sufficient conditions for Radial OD requirement, with % of baselines compliant; S/C 10°W, Variable tracking arc, swap scheduling, ranging interval

Tracking arc:	1 day			2 days			3 days		
Ranging interval [min]:	180	60	20	180	60	20	180	60	20
Station Swap: 12 hours									
Longitude Separation[°]	-	69.3	53.3	69.3	46.3	32.3	56.7	46.3	32.3
Latitude Separation [°]	-	17.8	14.1	17.8	13.2	8.9	15.7	10.8	7.4
Baseline within req. [%]	0.0	7.9	19.7	8.6	27.6	46.7	10.5	30.3	54.0
Station Swap: 6 hours									
Longitude Separation[°]	69.3	46.3	46.3	46.3	29.0	16.3	46.3	18.6	14.2
Latitude Separation [°]	15.7	14.1	10.3	13.2	7.8	4.1	11.6	5.9	4.1
Baseline within req. [%]	10.5	23.7	40.1	23.0	50.7	67.1	29.6	59.2	71.1
Station Swap: 3 hours									
Longitude Separation[°]	46.3	30.2	23.9	32.3	18.6	12.6	23.9	18.6	8.7
Latitude Separation [°]	14.1	11.6	5.9	10.1	5.9	4.1	7.8	5.1	3.1
Baseline within req. [%]	21.7	38.2	58.6	37.5	59.2	72.4	52.6	66.5	84.2

As it can be seen from those, a convenient ground station separation of less than 10° in longitude (8.7° allowing for more than 80% of the baselines to be considered) is possible.
The corresponding sufficient condition for latitude separation is 3.1°, or 5.8° for the great circle distance. This case has frequent ranging measurements (every 20 minutes) and stations' swap (every 3 hours) that are anyway both within the maximum capability of the ground segment design; In the phase of the procurement of tracking stations, it would be advantageous not to impose very large geographical separation between them, to allow wider open-competition with subsequent advantages from EUMETSAT point of view. Indeed, this would require a tracking arc of 3 days, which implies a relaxation of the original requirement of 24 hours. Due to the low frequency in the use of the dual-ranging OD during mission lifetime and that there is no impact on the space segment, the extended tracking arc (3 days) and the operational load of this case (3 hours swap with ranging every 20 minutes) have been considered acceptable; they will be used as reference case for the rest of the paper (without changes in tracking arc or tracking schedule).

7. Dual-Stations OD accuracy for variable Spacecraft Longitude (improved statistics)

Using the same approach of the previous section, the same analysis is repeated to consider the effect of the spacecraft longitude. A new database for TTC station, assuming as potential location all the main cities of EUMESAT member and cooperating states. This was done to further improve the statistical content (630 instead of 252 geometries), to augment the geographic coverage (except the far north of Europe that is not of interest due to antenna elevation limits) but also for fairness of the analysis towards all potential service suppliers. The new database is shown with equi-rectangular projection in Fig.7, where the city names are indicated with (m) for member and (c) for cooperating. To further expand the coverage, 4 additional entries are considered, whose name are marked with (a).

For the simulations of this set, considering the outcome of the previous section, only 1 tracking scheduling scheme has been considered : stations' swap every 3 hours, measurements every 20 minutes and 3 days tracking arc. The case with spacecraft at 10°West longitude (already considered before) is re-analysed with the extended stations' database. The results for the final OD accuracy (1-sigma) are shown in Fig.8 and Fig.9, respectively for the radial and along-track component of position, together with corresponding OD requirements (horizontal dash-dotted lines): radial position requirement 50m 3σ => 16.67m 1σ, along-track position requirement 1500m 3σ => 500m 1σ; the cross-track is similar to the radial, but less constraining, therefore not reported here; (in the figures, the angular range on x-axis has been reduced to 30° for practical visualisation reasons). The results are consistent with those obtained before: looking at the radial accuracy with spacecraft at 10°W (, left side, equivalent to the case previously analysed), one can see that the sufficient condition to fulfil the corresponding requirement are slightly bigger (due to the increased number of cases analysed), requiring about 12° in longitude and 4° in latitude separation respectively.

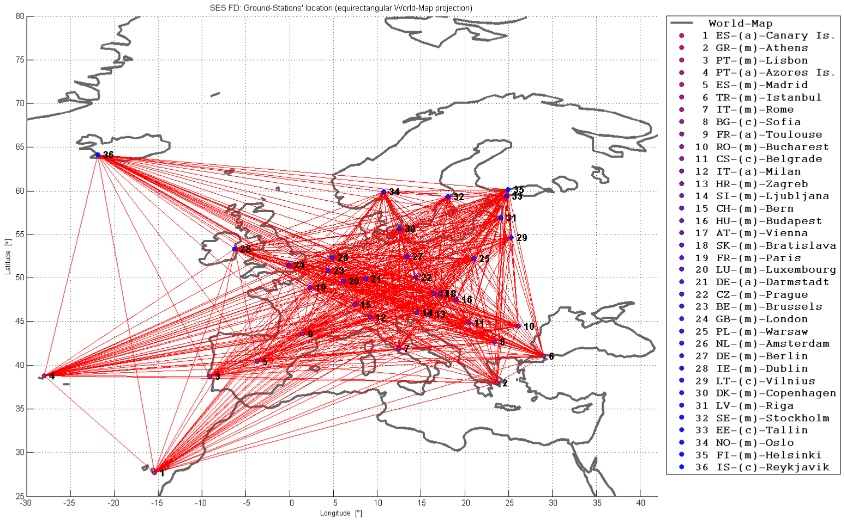

Figure 7: Baselines for initial assessment on dual-ranging OD

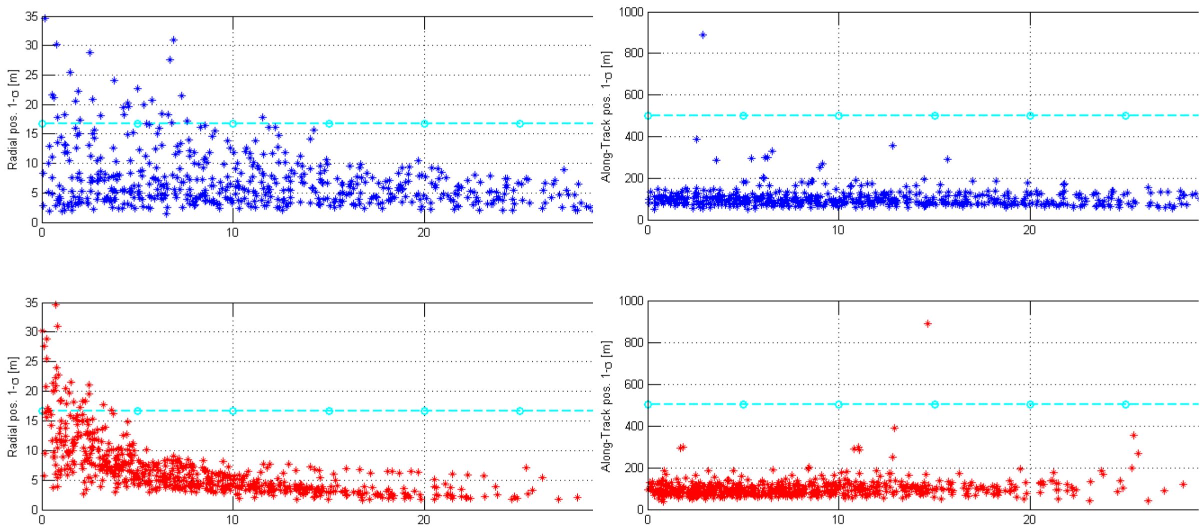

Figure 8: S/C at 10°WEST, OD results for Radial (left-side) and Along-Track (right-side), as function of baselines' longitude(top) and latitude(bottom) separation in [°]

From Fig.8, right side, it is interesting to note that the along-track requirement is fulfilled with good margin by almost all geometries, but there is one case not compliant. This corresponds to the baseline Lisbon-Dublin, whose vertexes have limited longitude separation with respect to the spacecraft longitude position. This effect is furthermore confirmed by the results of the simulation with the S/C at the opposite of the nominal longitude range, 10° East, as shown in Fig.9: from these results, the OD requirements on the radial position accuracy (left side) can be fulfilled by a longitude or latitude separation slightly less than the case with S/C at 10° West.
Looking at the along-track plots, there is an evident pattern for the longitude separation; this is a confirmation of the correspondent outcome of the previous case (S/C at 10°West), further consolidated by the fact that, with the spacecraft at 10°East, there are more geometries with limited longitude separation of the stations with respect to the longitude position. To cope with this, a specific longitude separation is also needed, in the order of magnitude of 7°.

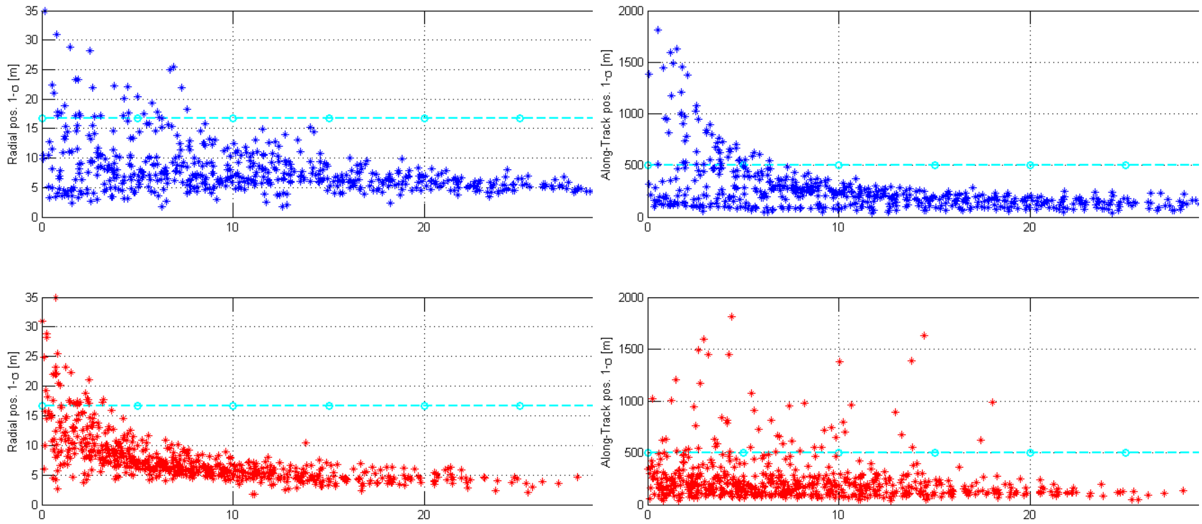

Figure 9: S/C at 10ºEAST, OD results for Radial (left-side) and Along-Track (right-side), as function of baselines' longitude(top) and latitude(bottom) separation in [º]

8. Theoretical analysis of OD accuracy

The results from the previous sections have been obtained with recursive runs of the covariance analysis, using all the permutations in a discrete set stations', as vertexes of the baseline. In support to this, and for a further improved characterisation and understanding of the results, it has been decided to perform a pure theoretical analysis on the OD accuracy: this would allow obtaining a continuous representation of the orbit determination, accuracy as function of the longitude and latitude separation between stations. The analytical models used in this phase are taken from [15], in the chapters related to "Tracking Geometry" (8.3) and "Tracking Observability and Accuracy" (8.7) for both single and dual-stations ranging. This model allows defining the achievable accuracy of an orbit determination, based on the simultaneous processing of ranging measurements, given an input noise on the measurements. The analytical formulation can be found in the reference book; hereafter few qualitative indications are given.
For a geosynchronous satellite, the orbital state can be efficiently represented by 6 the geosynchronous elements: λ(longitude), D(longitude drift-rate), e_x,e_y (2-D eccentricity vector)

and i_x,i_y (2-D inclination vector). The satellite λ and D can be determined from single-station ranging, provided the station and the satellite have different longitude; otherwise, the longitude and drift rate are not observable with ranging from a single station (even varying the station latitude): the process has here a singularity that would lead to infinite uncertainty in the determination. In case of dual-station ranging, if none of the stations has the same longitude of the spacecraft, there is tracking redundancy: this can be used in the estimation process, to solve for biases in one of the stations. To complete the determination of the orbital state, it is still necessary to determine the 4 remaining component of the geosynchronous elements. Considering the equations for tracking dependency on time and dual-stations ranging, it is possible to directly correlate the accuracy achievable in the OD with the ranging measurements noise and the geometry of the stations' baseline. The uncertainty obtained on the geosynchronous elements can be than converted on uncertainty in position and velocity in local-orbital frame (along-track, cross-track-radial), making use of the well-known Clohessy-Wiltshire formulas (see [16]), when considering the error on the orbital elements small with respect to the elements themselves (to allow linearization). This analytical model has a unique input error source (the ranging short-term noise); it is therefore a simplification of the more representative process that has been simulated before with the covariance analysis: in fact, the latter considered separately all different ranging error's contributors (short-term, periodic and long-term), as well as the effect of the different tracking schedules. It is anyway possible to "calibrate" the simplified model, choosing an input noise that gives a close representation of the already obtained results from the covariance analysis. This way, it is possible to have a qualitative analysis on the expected OD accuracy, for a continuous range of latitude and longitude separation between stations, given a fixed position of one of the two in the baseline.
This process has been followed, using as an example a fixed location of the 1st station at 10° longitude and 50° latitude (close to Darmstadt, where the EUMETSAT Headquarter is located) , for various spacecraft longitudes (between 10°W to 10°E); the results of the analytical model are represented as contour lines, showing the theoretical orbit determination accuracy achievable according to the location of the 2nd ground station, for the along-track, cross-track and radial position accuracy. As expected, the most demanding cases (from stations separation point of view) correspond to the radial case with the spacecraft at 10°W, and along-track case with the spacecraft at 10°E. They are shown respectively with equi-rectangular projection in Fig.10 and Fig.11: the white area around the 1st ground-station (GS-1) indicates the exclusion area for the location of the 2nd station in the baseline, to fulfil the requirements (contour lines are cleared).

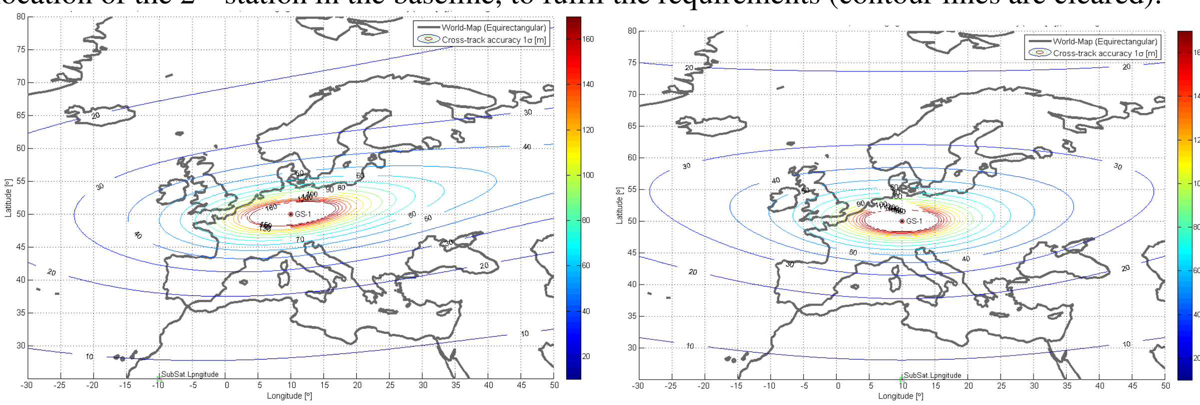

Figure 10: Contour lines, OD Radial position accuracy (1σ[m],theoretical model), according to GS-2 location; Fixed GS-1(+10°,+50°); S/C at -10°(left), +10°(right) longit.

For the radial case in Fig.10, the exclusion area has the shape of an ellipse. From the analysis of the possible S/C longitude positioning between -10° and +10°, it can be concluded that:

- When GS-1 and S/C have the same longitude, the ellipse has: semi-major axis perpendicular to their meridian, axes dimensions minimum, centre in GS-1
- When the S/C is moved away from GS-1, the ellipse dimensions progressively increase; furthermore, given a certain displacement in the S/C longitude, the semi-major axis rotates with an angle opposite in sign, and the ellipse shifts in the opposite direction

For the along-track case in Fig.11, the exclusion area has the shape of a stripe, which is roughly constant in width, from the point of view of the great-circle distance; this gets distorted when represented in equi-rectangular map, due to convergence of the meridians towards the poles. From the analysis of all possible S/C location (-10° to +10° longitude), it can be concluded that:

- When the S/C and GS-1 have different longitude, the exclusion area has the shape of an ellipse with same behaviour of the one from the radial case, but always smaller
- When GS-1 and S/C have the same or close to the longitude, a north-south longitude exclusion stripe needs to be additionally superimposed (as also seen in the previous sections).

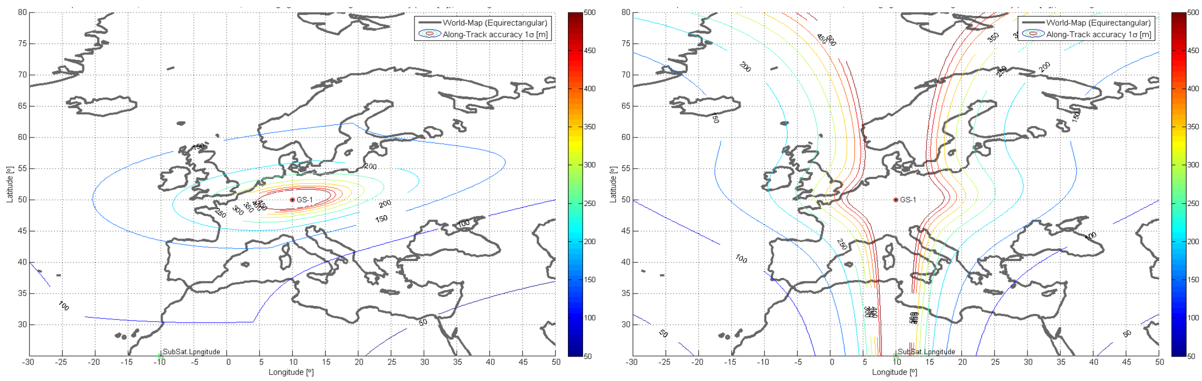

Figure 11: Contour lines, OD Along-Track position accuracy (1σ[m], theoretical model), according to GS-2 location; Fixed GS-1(+10°,+50°); S/C at -10°(left), +10°(right) longit.

The Cross-Track case is not shown, but the corresponding exclusion areas behave like the radial case (ellipse shape only, shirking/rotating/shifting) but always less extended in geographical dimensions with respect to the radial exclusion ellipse.
Supplementary analyses have been run, changing the location of GS-1 (specifically in latitude), confirming the qualitative conclusion above; the added remark is that, as expected, due to the effect of converging meridians, the whole geometry requirements for longitude separation expand or retract as GS-1 moves northwards or southwards respectively; same for the overall dimensions of the exclusion ellipse (expanding when GS-1 is moved northwards, and translating as well the centre along the semi-major axis).

9. Formulation and cross-verification of the stations' separation requirements

From all the analysis presented at this point, it can be concluded that the requirements for the geographical separations of the 2 TTC ranging stations can be conveniently expressed as an exclusion area with the shape of an ellipse (mainly driven by the demanding radial accuracy requirements) with a North-South exclusion stripe (driven by the along-track accuracy) that anyway has to be considered only when the location of the primary station is close to the nominal longitude range of the S/C.

This can be summarised by the following 2 conditions:

$$\frac{\left[(x_2 - x_1)\cdot\cos(c) + (y_2 - y_1)\cdot\sin(c) + d\right]^2}{a^2} + \frac{\left[-(x_2 - x_1)\cdot\sin(c) + (y_2 - y_1)\cdot\cos(c)\right]^2}{b^2} > 1 \qquad (1)$$

$$if\ \left|x_1 - x_{s0}\right| < \left(e + x_{sm}\right),\ then\ \left|x_2 - x_1\right| > f \qquad (2)$$

$x_{1,2}$	=longitude of TTC-1,2;	a,b	=semi-major, semi-minor axis;
$y_{1,2}$	=latitude of TTC-1,2;	c	=ellipse rotation angle
x_{s0}	=centre of S/C longitude range;	d	=longitude shift of ellipse centre
x_{sm}	=max. longitude excursion from x_{s0};	e	=north-south stripe longitude distance
		f	= north-south stripe longitude width

All the coefficients in Eq.1 and Eq.2 are in [°], except for *c*, in [rad]. Equation 1 represents a conditional statement, to be considered only when the tracking station geometry is close to the spacecraft nominal longitude range. *a,b,c,d,e,f* are empiric functions whose numerical coefficients are obtained from the theoretical analysis above. They take into account the longitude distance from the stations and x_{s0}, and also the latitude the first stations.
The location of the stations should be also compatible with the antenna elevation limit (typically 13° (as show by the thick line in Fig.2).
The covariance analysis module has been used finally again, to cross-verify the formulated requirements on ground stations separation. In this case, the location of the primary ground station (GS-1) is selected; then, a regular grid of hypothetical secondary ground stations (GS-2) is generated: the grid is equi-spaced in longitude and latitude around GS-1. For each baseline formed by the fixed GS-1 and the various GS-2 from the grid, a full covariance analysis is run. The results of this discrete analysis are then interpolated using a bi-cubic method, to improve the resolution. The OD accuracy resulting from this process are the compared back with the

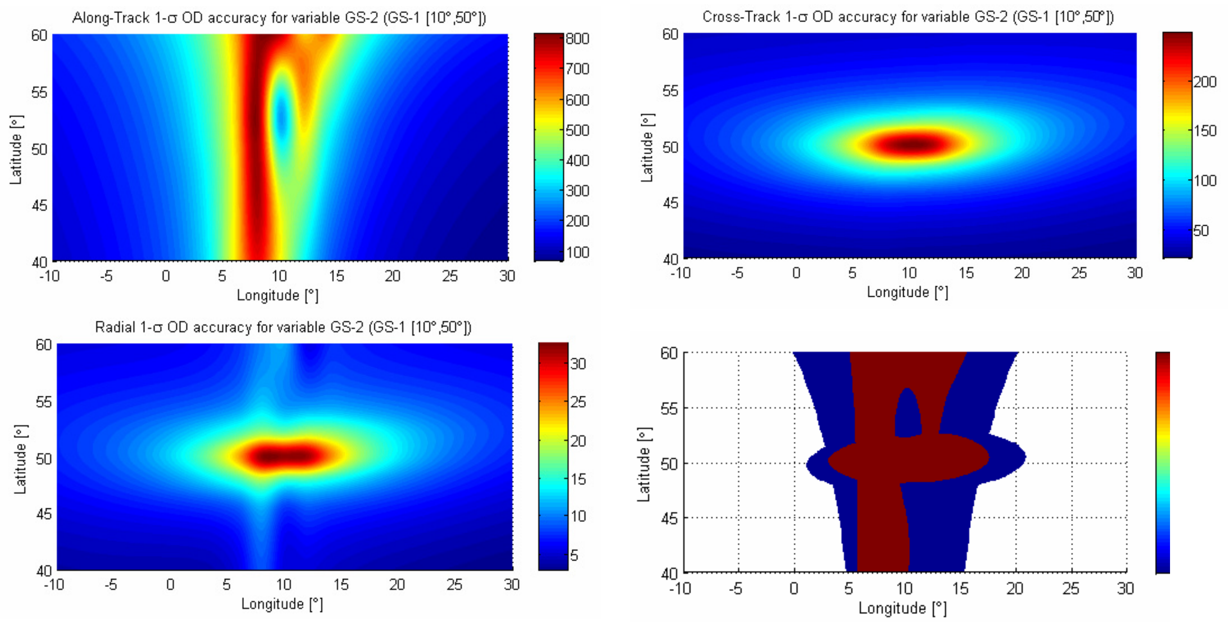

Figure 12: Example of cross-verification of the empiric formulas for ranging station separation; Fixed GS-1 location (+10°, +50°); S/C at +5° longitude

correspondent required accuracy, to identify the area not compliant for each of the components. The actual exclusion area (as from covariance analysis) can be obtained as union of the single along-track, cross-track and radial exclusion areas. This merged exclusion area can be then compared back with the one obtained from the formulas above, to ensure that the first is contained within the second.

An example of this analysis is given in Fig.12: the bottom-right plot shows in red the super-imposition of the exclusion areas from the other 3 plots (for those location above the respective required OD accuracy), while the blue area is the exclusion zone coming from the analytical formulation of the stations' separation, from Eq.1 and Eq.2.

The same method has been applied for various location of GS-1, also changing the S/C longitude position, fully validating the formulated analytical conditions for the stations' separations.

10. Conclusions

The MTG system has demanding requirements for the accuracy of the orbit determination, especially for the accuracy of the estimated radial position. This paper focused on one of two different orbit-determination schemes that are foreseen during operations: traditional dual-ranging, used for INR initialisation. Initially, different tracking scheduling schemes have been investigated (with various station swaps and interval between ranging measurements) using a tool for accurate simulation of the orbit determination process, based on covariance analysis. This step demonstrated that even in case of maximum system load (frequent swap and measurements), the required orbit determination accuracy can be achieved with a convenient separation between the ranging stations, only in case of an extended tracking arc of 3 days duration. This implied a change the original MTG system requirements, to accommodate a longer period for INR initialisation. The second part of the paper focused on the formulation of the requirements for the separation of the ranging stations. In this case, a combination of covariance analyses and theoretical models has been used. This led to the identification of empiric formulas for the stations' separation, representing exclusion areas as an ellipse with superimposed north-south stripe; these can be formulated as a function of longitude and latitude separation between the stations, as well as the longitude distance of the baseline with respect to the spacecraft longitude location. The accurate definition of these areas is an asset for the MTG programme, as it will promote increased competition in the procurement of the ranging stations, avoiding unnecessary over-constraining. The methods adopted and the results obtained in this paper are of interest for geosynchronous missions based on traditional dual-ranging techniques.

11. Acknowledgements

The authors thank the company DEIMOS Space, S.L.U., for their efficient and invaluable work and effort in the provision of the TRAMOS tool, briefly introduced in section 4. of this paper, and so much used and exploited in the frame of EUMETSAT internal mission analyses for orbit determination accuracy.

12. References

[1] EUMETSAT web site: http://www.eumetsat.int/Home/Main/AboutEUMETSAT/index.htm?l=en

[2] Meteosat Third Generation, Satellites overview: http://www.eumetsat.int/Home/Main/Satellites/MeteosatThirdGeneration/index.htm?l=en

[3] S.Rota "Monitoring Weather And Climate From The Geostationary Orbit: The Meteosat Third Generation (Mtg) Programme", IAC-12.B1.1.1, IAC2012, Italy

[4] MTG Operations Baseline Requirements Document [OBRD], EUM/MTG/SPE/10/0456 http://www.eumetsat.int/Home/Main/Satellites/MeteosatThirdGeneration/Resources

[5] Kinter, H., Righetti, P., Raballand F., Lagadec K., "Meteosat Third Generation Mission feasibility for Orbit and Attitude", SpaceOps 2008, May 2008, Heidelberg, Germany.

[6] Kinter H., Mullet B., Just D., "Meteosat Third Generation Navigation Approach", 22nd ISSFD , March 2011, São José dos Campos, Brazil.

[7] Righetti P., Kinter H., "Feasibility of MTG Collocation using a Single S-band Tracking Station and Large Inclination Manoeuvres", 22ndISSFD, March 2011, S.José dos Campos, Brazil.

[8] De Juana J. M., Meixner H., Mullet B., "The challenges associated with Meteosat Third Generation Collocation Strategies", SpaceOps 2010, Apr. 2010, Huntsville (Alabama), USA.

[9] Bierman G.J., "Factorisation Methods for Discrete Sequential Estimation", Mathematics in Science and Engineering, Vol. 128, Academic Press, 1977.

[10] International Reference Ionosphere (IRI): http://modelweb.gsfc.nasa.gov/ionos/iri.html

[11] Jakowski N. et al. , "Total electron content models and their use in ionosphere monitoring", Radio Science, Vol. 46.

[12] Space Weather Application Centre - Ionosphere (SWACI) : http://swaciweb.dlr.de

[13] J. Harris, "Study on Image Navigation & Registration for Imagery & Sounding Observations", Final Report, Issue 1, EUMETSAT CO/o7/4600000364/DJ, January 2008

[14] J. Harris,D. Just, "INR Performance Simulations for MTG", SpaceOps, USA, April 2010

[15] E. M. Soop, "Handbook of Geostationary Orbits", 1994, Series: Space Technology Library, Vol. 3, Springer, ISBN 978-0-7923-3054-7 , pp.281-283.

[16] Clohessy, W. H., and Wiltshire, R.S., "Terminal guidance system for satellite rendezvous", Journal of Aerospace Science , Vol. 270, 1960, pp. 653-658.