Modelling ATV–TDRSS Communications at the International Space Station

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Introduction

This article describes an efficient way to model the radiation of S-band quadrifilar helix antennas mounted on the ATV and operating when it docks with the ISS. This electromagnetic modelling is particularly critical because of the overall dimensions of the ATV-ISS system vis-à-vis the S-band wavelengths and the continuous rotation of a number of solar-generator and thermal-radiator panels to track the Sun's position.

When the Automated Transfer Vehicle (ATV) docks with the International Space Station (ISS), the interactions between the ATV's S-band antennas and the large components (modules, solar panels, thermal radiators, etc.) of the ISS can significantly affect communication with the Tracking and Data Relay Satellite System (TDRSS) due to induced multipath effects. Extensive electromagnetic modelling has been used to establish that there will be sufficient margins for interference-free communication sessions during every ISS orbit.

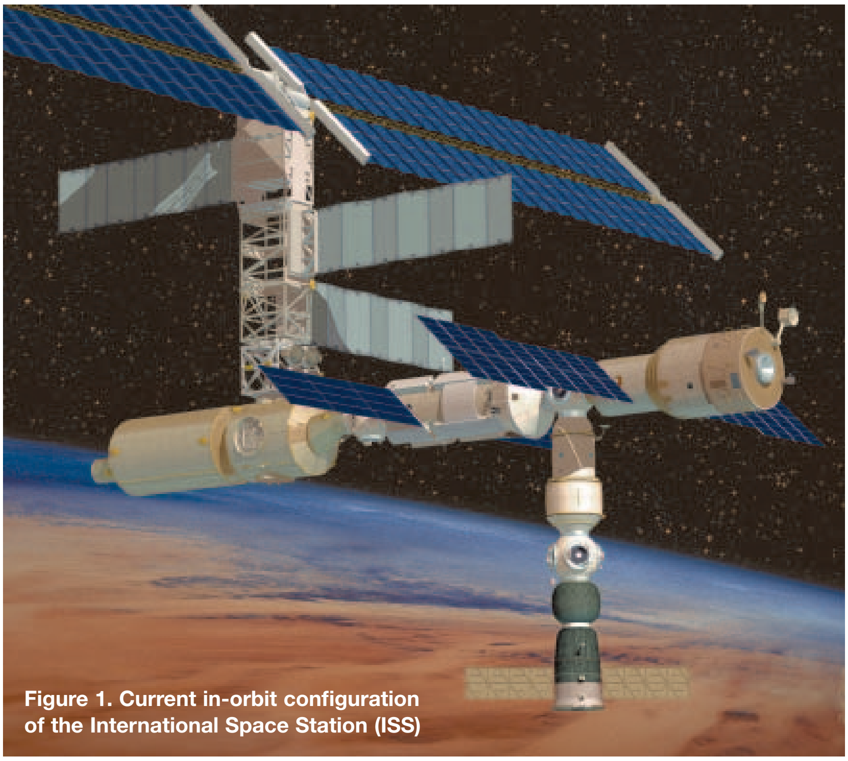


Figure 1. Current in-orbit configuration of the International Space Station (ISS)

The ISS is currently being assembled in orbit around the Earth (Fig. 1) and, when completed around 2006, the huge complex will be the largest ever structure in space, stretching over 100 metres and sprawling across an area the size of a modern football stadium.

ESA, NASA and the Russian, Japanese and Canadian Space Agencies are the international partners involved in the project. In addition to serving as a base for future space exploration, the ISS will be a laboratory for the scientific community where weightlessness and the unique environment of space will open up new areas for long-term research, including medical studies and the development of materials and manufacturing processes not possible on Earth. The main characteristics of the ISS are summarised in Table 1.

Table 1. Main characteristics of the ISS

Partners	USA, Russia, Europe, Canada, Japan
Laboratories	Six
Permanent Crew Capacity	Six/seven
Orbit	90 minutes to circle Earth
Inclination	51.6° to the Equator
Altitude	400 km (average) above Earth
Dimensions	108 m long x 80 m wide
Mass (weight)	455 865 kg
Living Volume	1200 m^3

The ATV is a large Automated Transfer Vehicle to supply the ISS. This new vehicle (Fig. 2), scheduled for an initial test flight in 2004 on Ariane-5, will dock with the Station's Russian Service Module. The ATV weighs 21 750 kg at launch, including 9500 kg of payload that includes food, water and oxygen for the crew, instruments and hardware for the Station, and propellant. Some 4000 kg of the propellant will be used to re-boost the Station to a higher orbit at regular intervals; another 860 kg will be transferred to the Station for its own attitude and orbit control. Like a classical spacecraft, the ATV is equipped with avionics, navigation and propulsion, and powered by solar panels. It will carry a separate pressurised payload container to which the crew will have access when docked to the Station (Fig. 3).

An accurate electromagnetic simulator

Most of the previous electromagnetic studies devoted to this topic were based on simple geometrical models obtained by replacing the entire structure, composed of the ATV and the ISS, with only the largest components (less than ten elements). Consequently, the interactions between the ATV and ISS had been simulated with only limited accuracy. The first step in our analysis was therefore the generation of a new geometrical model composed of around one hundred elements, including all of the solar panels, all of the thermal radiators and the main modules making up the ATV and the ISS (Figs. 4 and 5).

In particular, in Figure 5 the y-axis is oriented along the central truss of the ISS, the x-axis is oriented like the ATV's x-axis along the velocity vector, whilst the z-axis, oriented to Earth, is perpendicular in the chosen view to the solar panels. The ATV appears in orange on the left side, the large American solar panels are in blue, with their main axis x-oriented, the Russian solar panels, which are y-oriented, are also in blue, and the large thermal radiators are shown in black (in two planes parallel to the plane y = 0).

It is important to note that while flying around the Earth the ISS continuously assumes a different orientation with respect to the position of the Sun. Consequently, in order to track the Sun, the solar panels and thermal radiators have to rotate to remain, respectively, perpendicular and parallel to the Sun's rays. Figure 5 actually relates to an extreme case in which the Sun lies exactly in the direction of the –z axis.

Figure 2. The Automated Transfer Vehicle (ATV)

Figure 3. Artist's impression of the ATV docking with the ISS

Once a good geometrical model has been established, the second step was the realisation of the electromagnetic simulator. Firstly, this involved characterising the electromagnetic properties of the materials composing all of the modules, and then simulating the electromagnetic interactions between the ATV-mounted antennas and the metallic structures of both the ATV and ISS. In fact, the modules composing the ATV-ISS system can be considered perfectly conducting. The two sides of the solar panels exhibit different reflecting properties, the upper sides being composed of photovoltaic arrays, and the under sides being just a metallic surface. In our analysis, the solar panels and thermal radiators are also considered as perfectly conducting metallic plates characterised by a zero thickness.

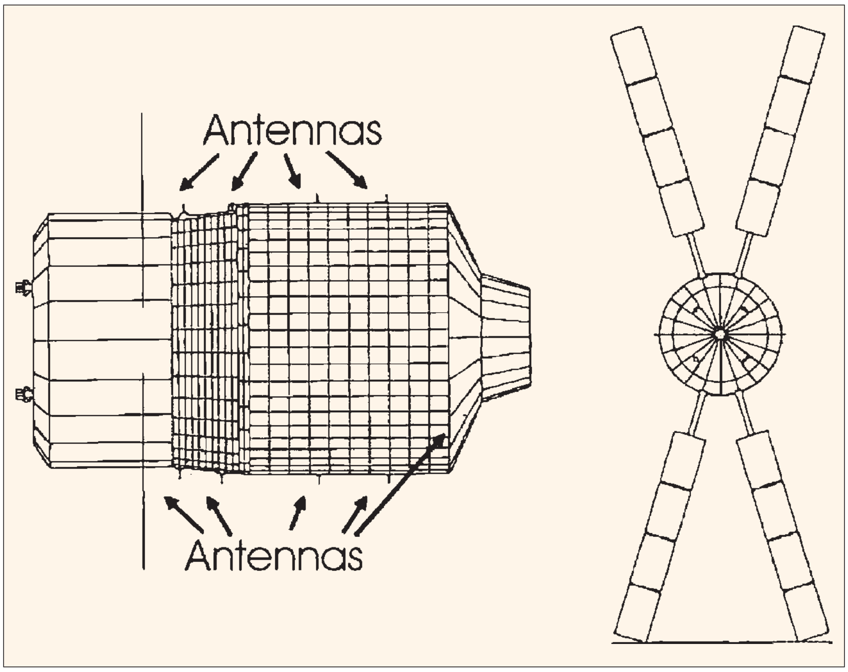


Figure 4. The geometrical modelling of the ATV and its antennas

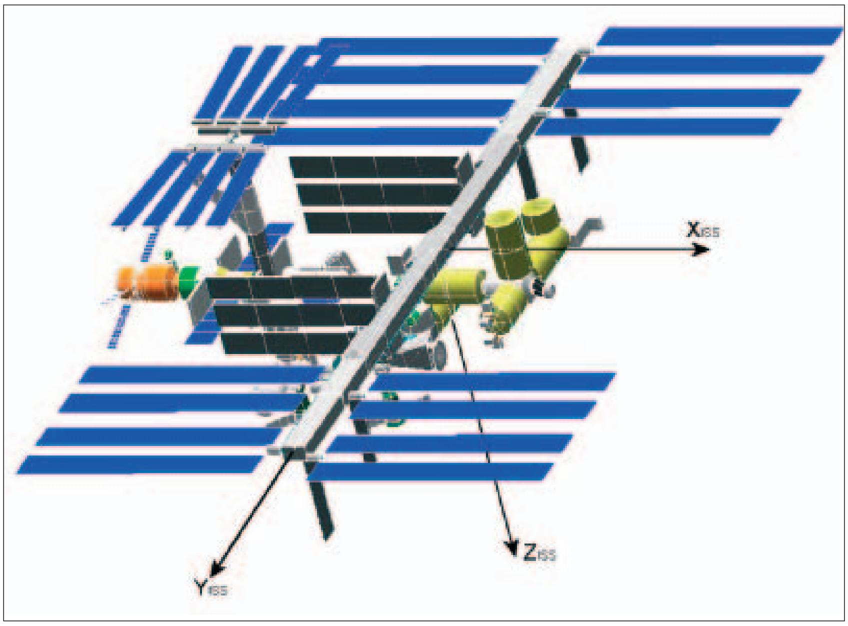


Figure 5. Elements included in the electromagnetic model of the ISS

Our work focused on the circularly polarised S-band antennas responsible linking the ATV-ISS and TDRSS systems. The frequencies chosen for the forward and return links were 2106.4 MHz and 2287.5 MHz, respectively. The antenna selected to establish the communications link was the quadrifilar helix unit shown in Figure 6. Its radiation pattern was shown in several experimental tests, performed by Astrium and RYMSA, to suffer only weak degradations in the presence of the ATV structure. The measured pattern of the isolated helix antenna was compared with that for the same antenna mounted over a cylindrical mock-up structure simulating part of the ATV module.

The ATV and the ISS are too large, in terms of wavelengths, for a rigorous full-wave analysis to be implemented. However, the ray-based Uniform Geometrical Theory of Diffraction (UTD) is particularly suited to managing the interactions between large structures that include metallic plates, cylinders, cones and similar components. The commercial code NEC-BSC IV (by Ronald J. Marhefka of Ohio State Univ.) allows one to take into account several ray contributions, including multiple reflections, diffractions from edges, wedges, corners, etc. (Fig. 7).

The speed of the electromagnetic simulator is particularly important in this type of analysis because the radiation from the S-band antennas has to be estimated for several possible orientations of the solar panels and thermal radiators as they continuously rotate. To introduce the S-band antennas into the electromagnetic characterisation, the measured radiation pattern relevant to the free-space helix antenna has been inserted in the UTD analysis as an equivalent source located

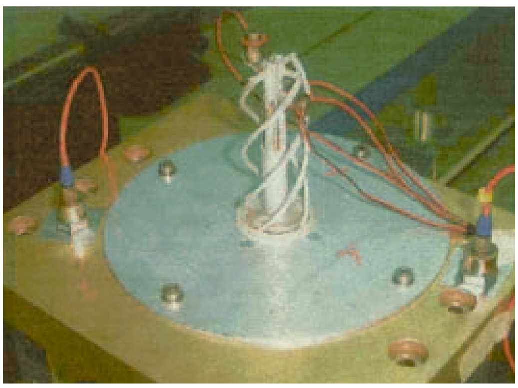


Figure 6. The quadrifilar helix antenna on the ATV

exactly where the antenna is sited. This can be considered a hybrid UTD-measuring technique.

It has been verified (by EADS and Astrium) that, by evaluating the UTD interactions between the equivalent source and a cylindrical metallic mock-up, one obtains results really close to the measured results relevant to the configuration composed by the real helix antenna and the mock-up.

As previously mentioned, to completely characterise the radiation properties of the S-band antennas mounted on the ATV, a great number of simulations, corresponding to different orientation of the solar panels and thermal radiators, are required. The calculation times needed to run the electromagnetic simulations are therefore extremely important and the UTD modelling procedure was selected also for this reason.

It is important at this point to introduce three elements that play a significant role in the radiation mechanism, because of their proximity to the ATV. They are: (i) the vertical white mast shown in Figure 7, which is the Science Power Platform (SPP) core, a Russian supporting element; (ii) the Russian solar panels, which are the small horizontal blue panels near the TDRSS satellite at the top of the figure; and (iii) the Russian SPP thermal radiator, which is the horizontal rectangular component made with six rectangular plates. In several cases, these Russian elements create more electromagnetic interference than the huge American solar panels (the large blue panels with an oblique orientation in Fig. 7) located further from the ATV.

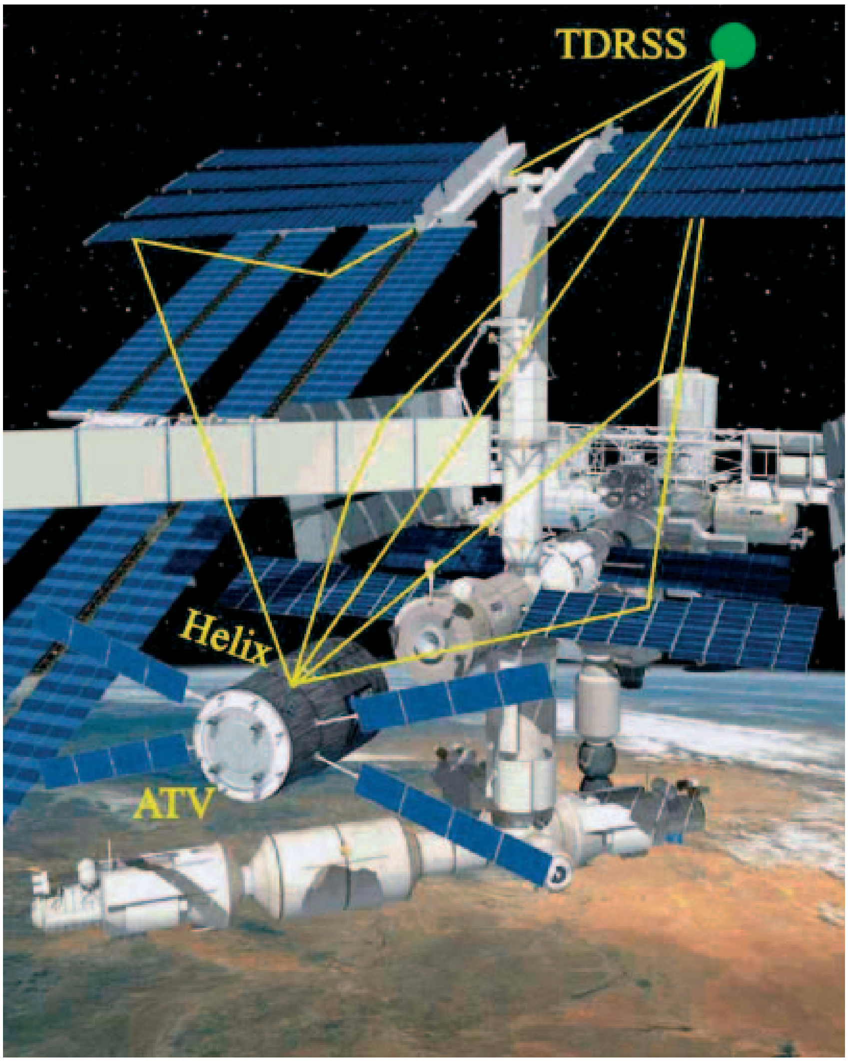


Figure 7. Some possible ray contributions in the link between the ATV and TDRSS

Electromagnetic fields radiated by the S-band antennas

As the ATV-ISS system orbits the Earth, its z-axis is normally Earth-oriented and its x-axis oriented along the trajectory. For the present study, therefore, it is interesting to simulate essentially the field radiated in the half-space characterised by $z < 0$, where the satellites to be linked with the ATV-ISS system are usually located. This is why, in the following figures, the UTD simulated results are only visualised in this half-space.

Figure 8 is a three-dimensional view of the co-polarised and cross-polarised components radiated by the quadrifilar helix antenna mounted on the ATV docked on the ISS, for the case with horizontal solar panels (panels located in the x-y plane). The vertical scale denotes the directivity, and the horizontal scale denotes the angle θ measured from the (–z) axis; the circular scale denotes the angle ϕ measured from the x-axis in the direction of the y-axis. A circle at $\theta = 70°$ has been superimposed to indicate the angular region in which the ATV antennas have usually to guarantee coverage.

For the co-polarised component (on the left), the blue zones represent the region shadowed by the ISS. In particular, the blue horizontal area indicated by the number 1, represents the shadow of the Russian mast supporting the Russian solar panels. The vertical light-blue area, indicated by the number 2, represents the shadow of the Russian solar panels, while the blue curved area indicated by the number 3 represents the shadow of the vertical thermal radiator attached to the Russian mast. In this particular case, with all solar panels perpendicular to the z-axis, the large American solar panels slightly modify the pattern of the helix antenna. Their shadow is evident only near the border of the circle, i.e. for θ near 90°. Observing the cross-polarised component (right), one can see that it is larger than the corresponding free-space component and that this image is relatively noisy. It is interesting to note that the red area, indicated by the number

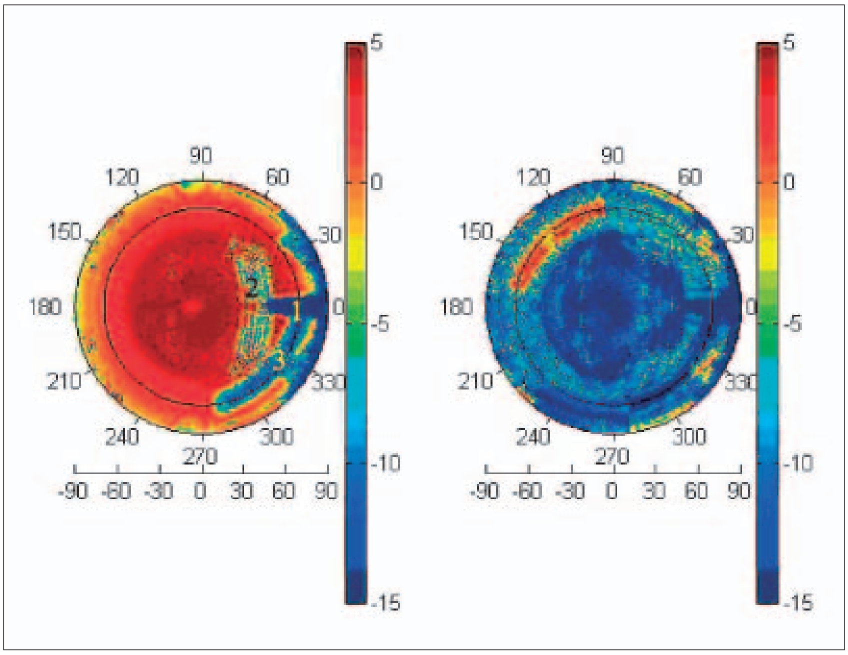


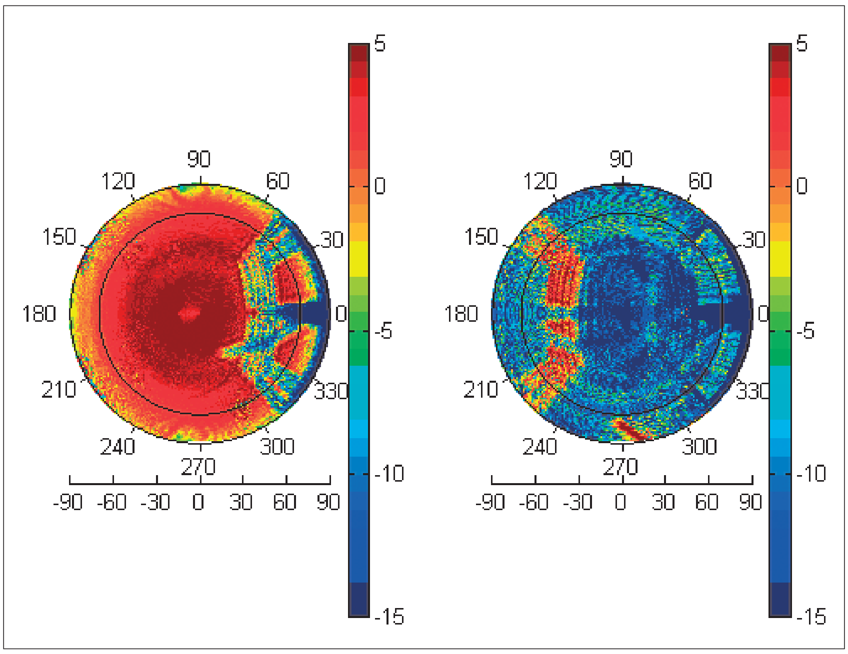
Figure 8. Representation of the co-polarised (left) and cross-polarised (right) radiation from the helix antenna mounted on the ATV docked on the ISS, with solar panels horizontal

4, is due to the reflection on the vertical thermal radiator. This reflection contribution is particularly evident in the cross-polarised component.

Figure 8 shows that the Russian mast, the vertical thermal radiator and the Russian solar panels create important scattering contributions in the radiated pattern. Despite the fact that these Russian appendages are smaller than the American ones, because of their position near the ATV and because they are located exactly in the half space where the TDRSS satellites are normally positioned, their structures will always modify the pattern of the helix antennas.

Figure 9 shows the same quantities as plotted in Figure 8, but for the case when the solar panels are vertical (located in the plane y-z). One can see that in this case the American solar panels generate significant scattering contributions. For the cross-polarised components, the comments regarding the previous figure remain valid.

Figure 9. Representation of the co-polarised (left) and cross-polarised (right) radiation from the helix antenna mounted on the ATV docked to the ISS, with solar panels vertical



Electromagnetic fields received by the TDRSS satellites

Once a good electromagnetic modelling tool has been established, the electromagnetic field received by the three geostationary TDRSS satellites can be estimated, based on the following steps:

- The Sun's trajectory with respect to the ATV-ISS system was studied.
- The trajectories of the TDRSS satellites with respect to the ATV-ISS system were analysed.
- Some critical cases were selected and the signal arriving at the TDRSS satellites estimated and compared with that reaching the satellites when neglecting the ISS effects.
- Due to the difficulties of obtaining other reference data, a simple Geometrical Optics (GO) simulator to evaluate the shadowing effects associated with the main appendages of the ISS for every trajectory was also implemented. Its results were in good agreement with those obtained with the more rigorous simulator introduced previously. This test provided a cross-check on the simulator's accuracy.
- An estimation of the time available to establish the ATV-TDRSS connection was finally obtained.

During every Earth orbit, the ATV establishes a link with every TDRSS satellite, one after the other. However, in every instance the link could be established with two of them. To choose the best satellite, the angle between the helix-antenna axis and the direction to every satellite is continuously evaluated and the satellite associated with the minimum angle selected to maintain the strongest radiated antenna signal. This is essentially the same procedure followed by the S-band antennas to track the TDRSS satellite. Several cases have been analysed and the conditions under which the appendages of the ISS particularly disturb the link ATV-TDRSS have been identified.

First of all, the trajectories of the three TDRSS satellites with respect to the ATV-ISS composite have been studied. An interesting and important property of the trajectories of the three satellites has been evidenced. When a TDRSS satellite trajectory is projected on the two-dimensional colour plot representing the pattern of the S-band antennas in z < 0 half-space (Fig. 10), one obtains an arc.

This type of visualisation is very useful for identifying the most critical trajectories before performing the complete electromagnetic analysis. The worst trajectories are those that intersect more the blue areas representing the shadow regions. The blue areas are the regions where the radiation from the ATV antennas, blocked by the presence of the ISS, does not ensure an electromagnetic coverage towards the data relay satellites.

In Figure 10, the electromagnetic field represented has been obtained by only including the geometrical shadowing effects due to the ISS: these are the dominant effects in the co-polarised component. The three trajectories relate to the three TDRSS satellites. In particular, the yellow curve refers to satellite number 1, the green curve to satellite number 2, and the magenta curve to satellite number 3. The geostationary orbits of these three satellites are characterised by three fixed angles with respect to the Greenwich meridian: 41°W, 174°W and 275°W.

In Figure 10, the three trajectories cross the blue shadowed regions, with a corresponding reduction in signal intensities. This graphical analysis is useful, but it is important to remember that the orientation of the panels continuously changes to track the Sun, and that the blue shadow is only relevant to one possible orientation. When varying the orientation of the panels, the blue shadow regions change but they are always located in the right-hand part of the plot.

The positions of the trajectories depend on several factors: the date, the hour and a certain angle Ω_0 defining the angular distance, along the equator, between the starting point of the ISS trajectory and the γ point (defined with respect to the Aries constellation). Once these time and geometrical parameters have been defined, the trajectory can be exactly positioned with respect to both the Sun and the TDRSS satellites.

The most critical trajectories have been plotted in Figure 10. One projected trajectory is exactly parallel to the 0° azimuth direction. This is the case in which the fixed part of the ISS and, in particular, the Russian mast, is shadowing one TDRSS satellite. The other two satellites remain possible targets for the shadow relevant to the moving solar panels. Physically, this condition only occurs in the particular case in which the ISS, crossing the equator, is linked with a TDRSS satellite with exactly the same longitude as the crossing point. Starting from the knowledge of all the geometrical and temporal parameters, the link between the ATV-ISS system and the TDRSS satellites has been studied. A detailed analysis of the electromagnetic results relevant to the conditions shown in the Figure 10 is presented below.

In Figure 11 the case corresponding to Figure 10 is analysed. The abscissa θ represents the orbit angle, the so-called 'true anomaly', ranging from 0° to 360°. The angular range corresponds to an entire orbit of the ISS around the Earth. Figure 11a shows which TDRSS satellite is linked to the Space Station during a particular orbit. In these figures, the background colours denote the TDRSS satellite linked at each particular moment to the Station: yellow refers to TDRSS satellite number 1, green to satellite number 2, and magenta to satellite number 3.

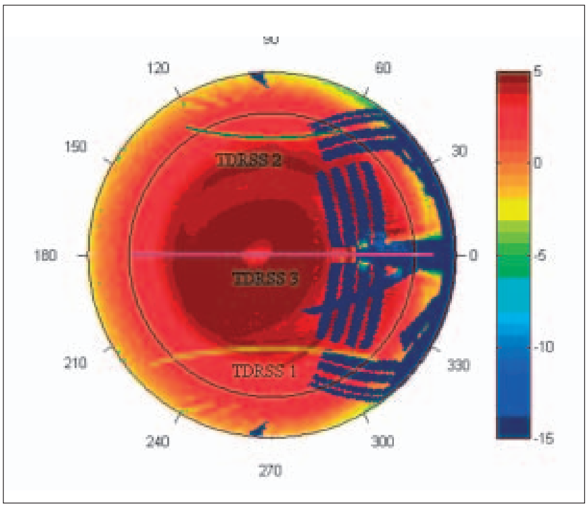


Figure 10. Radiation of the ATV helix antenna towards the relay satellites, showing the shadow of the ISS. Possible data-relay-satellite trajectories are shown

In Figure 11b, the co-polarised component of the field radiated from the ATV-ISS system, evaluated exactly at the TDRSS position, is plotted with respect to the corresponding component obtained by only considering the ATV in the absence of the ISS. Figure 11c is relevant to the cross-polarised components, where the signals are less strong but present a larger dynamic range. Figure 11d represents the occurrence along the same trajectory of geometrical shadowing effects due to the American solar panels, the Russian solar panels, the Russian mast supporting the Russian panels, and the SPP thermal radiator. The ordinate value 0 denotes no shadowing effect; the value 1 indicates that shadowing occurs. Some agreement exists between this elementary Geometrical Optics model and the rigorous results plotted in Figure 11b. All data have been obtained using one point every 5°, which is equivalent to sampling the signal every 1 min and 15 sec.

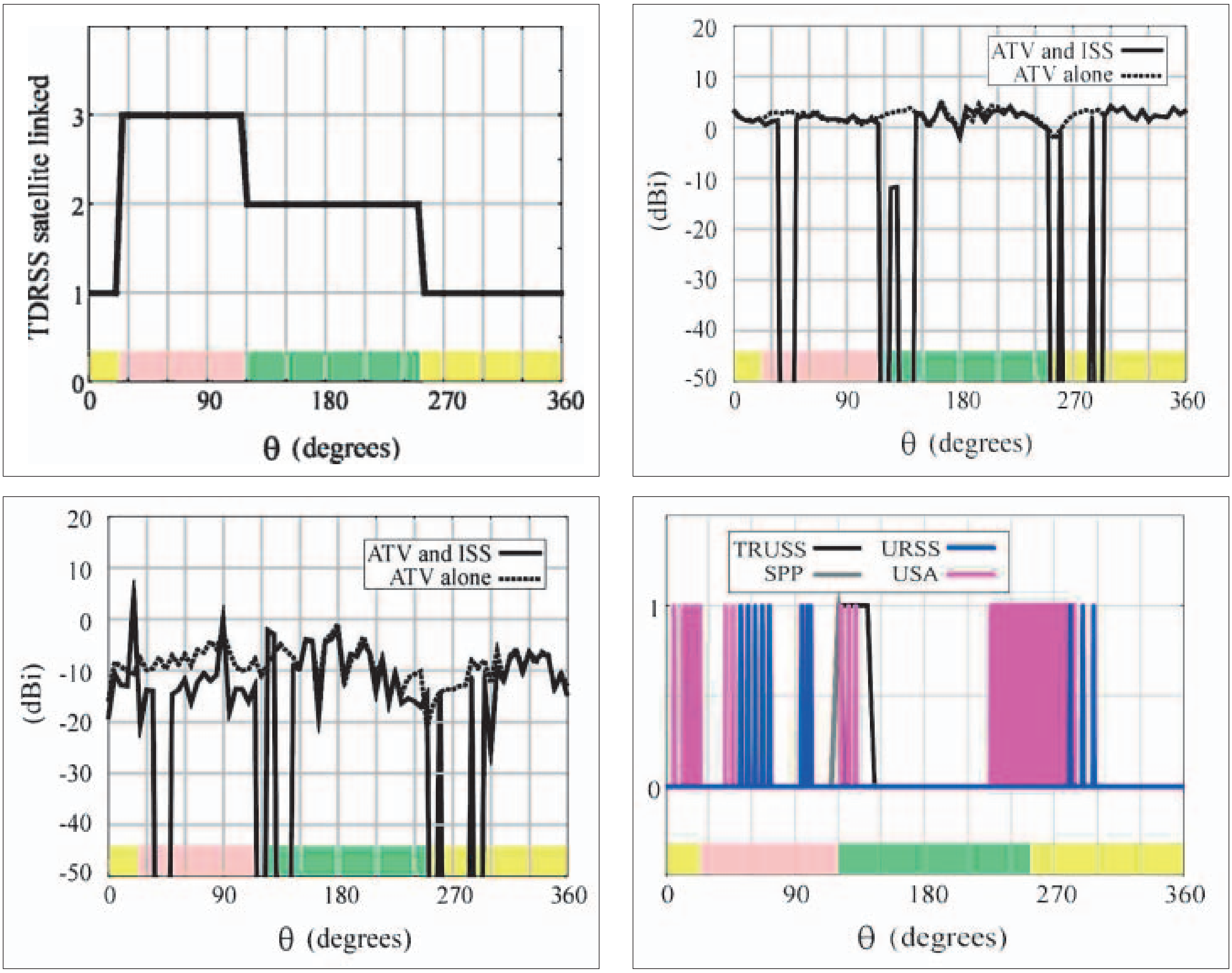


Figure 11. Detailed analysis of the ATV-TDRSS link - the worst-case scenarios for: (a) TDRSS satellites linked to ISS in one orbit (b) Co-polarised signal at TDRSS with and without ISS (c) Cross-polarised signal at TDRSS with and without ISS (d) Elements of ISS shadowing the ATV-TDRSS link

Figure 11, which represents one of the worst-case scenarios, shows that around 3/4 of the entire trajectory can be considered safe to establish the link: this means that some 67 minutes are available for the link, and only 23 cannot be used. It can be seen in the previous figures that the direct link is interrupted at least three times during every ISS orbit. Hence, at least 22 minutes of link time are always available, which is more than twice the 10 minutes required. This confirmation represents the main result of our study.

Conclusions

Our study has demonstrated that for every orbit of the ATV-ISS system, there will be sufficient margins to establish a direct link with the TDRSS satellites. Some 67 minutes per orbit can be used to establish the ATV-TDRSS link and at least 22 minutes are available for a continuous link.

Compared to the previously available electromagnetic simulators, the tool that has been developed is much more accurate because of the better geometrical description of the ATV-ISS system, because of the higher-order interaction effects considered in the analysis, and because the position of the Sun and the TDRSS with respect to the orbiting ATV-ISS system has been carefully taken into account. The new electromagnetic simulator can also be used to study the rendezvous phase in which the ATV is approaching the ISS and the link between the ATV and the Global Positioning System (GPS) satellites. The new simulator can also be easily modified for analysing other electromagnetic links involving antennas working at different frequencies and located elsewhere on the ISS structure, and also for the design and positioning of those antennas.