Usage of IGS TEC Maps to explain RF Link Degradations by Spread-F, observed on Cluster and other ESA Spacecraft

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ABSTRACT

During autumn and spring 2001, 2002 and 2003 link degradations up to complete signal loss were observed on the Cluster spacecraft: Sudden variations of the received RF signal power were observed on the spacecraft as well as on the ground. The duration of these disturbances ranged from 10 minutes to 4.5 hours, i.e. up to a loss of entire spacecraft passes. The anomaly coincides with the local evening hours and depends on geographical location of the ground station.

A multi-disciplinary working group at the European Space Operations Centre (ESOC) with support from scientists at European Space Technology Centre (ESTEC) was set up to investigate and could identify a phenomenon in the ionosphere, Spread-F, as source of the anomalies. Spread-F can occur around the geomagnetic equator during the local evening hours. IGS TEC maps were used to identify the regions in the ionosphere where the Cluster-ground station links did cross the ionospheric shell and could in this way significantly contribute to the identification of the relationship between the observed phenomena and Spread-F. Spread-F is also often called plasma bubbles because they appear as density cavities in satellite observations. The diameter of the plasma bubbles is between 20 and 200 km.

RF link anomalies observed on other spacecraft, namely MSG-1 and XMM, could also be related to Spread-F. Based on the knowledge earned, the working group came up with recommendations for future missions and operations design.

1 INTRODUCTION

Link anomalies were observed on the Cluster spacecraft during autumn 2001 and 2002 using the Maspalomas and Villafranca ground stations (Smeds, 2002). A cross-disciplinary working group of experts at ESOC and ESTEC was established in January 2003 to investigate. This paper summarises the major findings of the working group (Billig et al., 2003) and regards the key role of IGS TEC maps (Feltens, 2003) aiding to identify the origin of the observed phenomena.

The anomaly consists of sudden variations of the received RF signal power levels, observed on the spacecraft as well as on the ground. For many of the cases the RF link dropped under the threshold and spacecraft data were lost. Problems with the used communications equipment on ground and on-board could be ruled out.

2 PROBLEM DESCRIPTION

2.1 *Characteristics of the Cluster mission*

Before describing the observed problem, some information is given about the Cluster mission.

The 4 Cluster spacecraft were launched in July/August 2000 into highly eccentric polar orbits with heights ranging between 18 000 km and 120 000 km. The spacecraft are spin stabilized, and the fleet flies in a formation achieving at one position in the orbit an ideal tetrahedron constellation. The inter-spacecraft distance was several times adjusted and ranged from 100 km to 5000 km up to now. The line of apsides of the mean orbit was initially in the ecliptic plane. Lunar and solar attraction cause the argument of perigee to increase yearly by about 5 degrees, i.e. the apogee to move southward.

Initially, from July 2000 to May 2002 only one ESA tracking site, Villafranca/Spain, was dedicated to the Cluster mission. The orbital period of about 57 hours results in an average visibility from one ground station in the order of 22 hours, subdivided into 2 – 3 passes of typically 10 hours length, for all 4 spacecraft per orbit.

Cluster is a non-realtime mission. All science data acquired during non-visibility periods are stored on the Solid State Recorder (SSR) and dumped to ground with a higher bit rate during the visibility periods.

Since the beginning of June 2002 the amount of science data acquired on board had duplicated requiring a second dedicated ground station. From mid May up to mid September 2002 Redu/Belgium was used as additional tracking site, before finally Maspalomas on the Canary Islands became the second ground station for Cluster. Nominally, Spacecraft 1 (SC1) and 2 (SC2) are allocated to Villafranca and Spacecraft 3 (SC3) and 4 (SC4) share the visibility to the Maspalomas ground station since then.

The Telemetry & Telecommand system operates in the frequency range of 2064 – 2077 MHz for uplink and 2242 – 2256 MHz for downlink. The downlink bit rate is selectable between 2 - 262 kbps. Nominally, only the high bit rate of 262 kbps is used for the SSR data dump during each pass.

2.2 *Observed phenomena*

2.2.1 AGC FLUCTUATIONS

The uplink power is monitored at each ground station. On-board, the received carrier level is monitored via the receiver Automatic Gain Control (AGC). The downlink signal is monitored on-board via the RF output power and on ground by the AGC level of the ground station.

When AGC fluctuations occur, several effects are seen simultaneously (Billig et al., 2003):

- The AGC level of the satellite receiver shows strong and fast fluctuations in both directions, i.e. increasing and decreasing signal strength with a variation of more than 10 dB peak-to-peak. An example is depicted in Figure 2-1**:** The on-board AGC readings obtained on 17 October 2002, the only day when on both stations and on all spacecraft fluctuations were observed.
- The AGC level of the ground station receiver shows the same behavior.
- If the variations are too strong, telemetry frames can get lost when the link margin has vanished. At this point spacecraft operations have to be halted, i.e. the data dump is stopped and the SSR is put into record mode, otherwise real time data and SSR data would get lost.

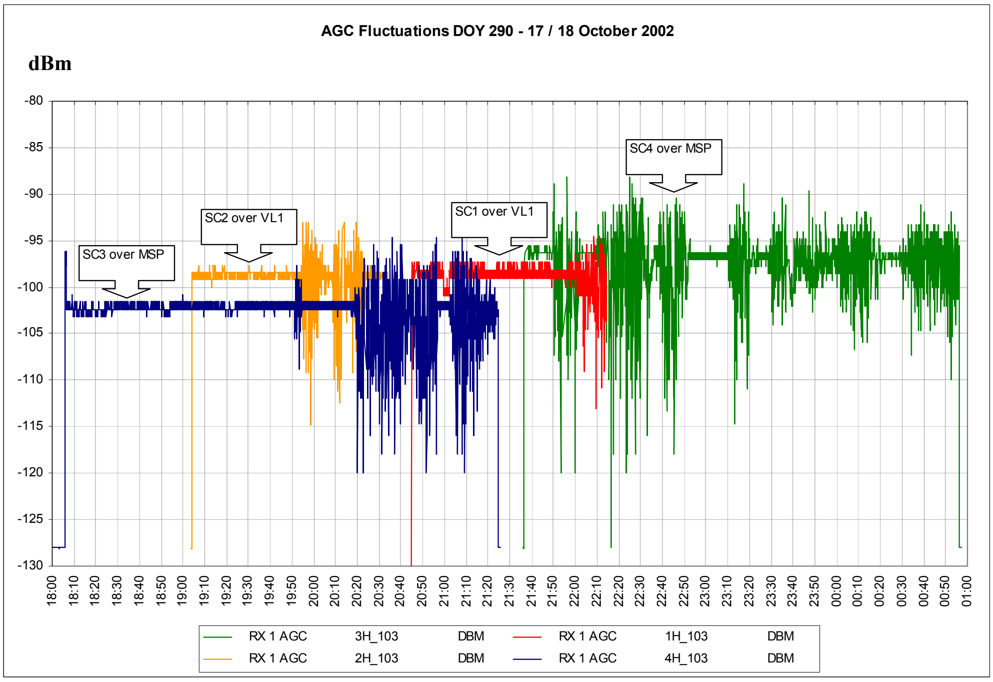

Figure 2-1: AGC fluctuations affecting serially all four Cluster SC on two different ground stations.

Having at apogee a link margin of 3 dB only, it is obvious that ground station passes with the spacecraft at apogee are the most susceptible against AGC fluctuations. To achieve the Cluster mission objectives it is vital that enough time is available to downlink the data stored in the SSR before they get overwritten.

The duration of these disturbances ranged from 10 minutes to 4.5 hours, i.e. entire spacecraft passes could not be used.

To describe the problem concisely, the influence of the geographic location of the ground station and the time of occurrence has to be discussed.

2.2.2 GROUND STATION LOCATION

As mentioned before, the Villafranca site was up to May 2002 the only Cluster dedicated station. Therefore, for this time no comparison with other ground sites can be made. In total 23 events are documented for year 2001 (this list might not be complete), equally effecting all 4 spacecraft. With 3 exceptions only, all disturbances were less than 1 hour long.

During the use of the Redu station, from mid May up to 15 September 2002, no fluctuations were observed, neither during Villafranca nor during Redu passes.

Simultaneously with the start of Maspalomas (MSP) support of SC3 and SC4 on 16 September 2002, strong AGC fluctuations affected a large number of passes. Of a total of 96 passes for SC3 and SC4, 33 have been affected between mid September and end of October 2002. Comparing the two stations, the Maspalomas passes for SC3 and SC4 show significantly more events than the Villafranca (VIL) passes for SC1 and SC2, as summarized in Table 2-1 below for the time interval 16 September to 31 December 2002. From this circumstance it can be concluded that there is a strong geographical influence.

	SC1 (VIL)	SC2 (VIL)	SC3 (MSP)	SC4 (MSP)
Passes with AGC fluctuations	3	1	31	23

Table 2-1: Number of passes with AGC fluctuations differentiating between spacecraft and ground station in use.

The observed problems are obviously denoted to the ground station location rather than to the satellite.

Analyzing the azimuth/elevation conditions of the passes with AGC fluctuations it was found that all passes with fluctuations as seen from Maspalomas were in a window with an elevation <60 degrees and the azimuth ranging between 90 - 240 degrees, i.e. into the southern direction.

The inspection of recent tracking data recorded at the Maspalomas station indicates an enhanced presence of AGC fluctuations also for the time interval September – December 2003. Again, the AGC fluctuation - scintillation appeared during the late evening hours between 19:00 and 02:00 UT, when the Maspalomas-antenna was pointing to South.

2.2.3 SEASONAL EFFECT / ORBITAL GEOMETRY

The screening through all documented events made it obvious that the vast majority (91%) had occurred between mid September and mid December 2002, and they appeared during the late evening hours between 19:50 to 02:00 UT. In these 3 months only at 2 times fluctuations occurred in the early morning hours up to 6:30 UT. The remaining 5 cases were observed between April and mid August in 2001. In 4 of those cases the fluctuation had occurred between 02:00 and 16:00 UT.

It is not straightforward to conclude from these observations that the AGC fluctuations are a seasonal effect. The Cluster orbit and its position of apogee relative to the Sun, depending on season, do influence the sampling of the events: 1) In winter, January - March, the majority of Cluster passes occur during day time. 2) In spring, April – June, most of the pass time is in the early morning up to mid day. 3) In summer, July – September, the majority of passes occur during night times. 4) In autumn, October – December, most of the pass time is in the late afternoon up to early morning. Such a ‘pre-selection’ of observation time might falsely point to a seasonal effect, if the events occur only at a certain daytime.

3 THE SPREAD-F PHENOMENON

3.1 Creation of Spread-F

Spread-F is often called “plasma bubbles” because they appear as density cavities in satellite observations. In reality, they are upwelling three-dimensional flux tubes of reduced plasma density (rising from the bottomside F-region) that are filled with enhanced plasma wave turbulence. After reaching the apex height in the geomagnetic equatorial plane around post-sunset, they move on either side of the geomagnetic equator along the field lines and break into small patches. The diameter of these plasma bubbles is between 20 and 200 km.

An electric field is generated along the equator due to the separation of electrons and ions by solar illumination. As already pointed out before, a movement of charged particles upwards and away from the geomagnetic equator is induced throughout the day (fountain effect). A change in this field impacts the conditions of the ionospheric cloud. At sunset the whole mechanism can get unstable, under certain conditions. A change of E-field influences the vertical motion of the electrons according to Lorentz force. Around 18:00 local time there can be a strong increase in the east-bound E-vector. The geomagnetic field is directed northward and the E-field eastward at the geomagnetic equator. Due to Lorentz force the ionospheric F-layer moves upwards, thus creating potential instability. Around 21:00 local time the E-field reverses and becomes directed to West. The Lorentz force causes the F-region to come down. Equatorial Spread-F now appears at the geomagnetic equator after sunset when the F-region moves to higher altitudes (> 400 km), where it then becomes unstable. The phenomenon can be explained as Rayleigh-Taylor instability (see e.g. Kelley, 1989). The triggering mechanism of Spread-F is, however, not yet completely understood.

3.2 Characterization of Spread-F

Strong Spread-F requires:

- A well-developed eastward electric field at the geomagnetic equator.
- A sharp raise of the F-layer's height around sunset (above ~ 400 km).
- Geomagnetic storms (induced by the Sun).

Dependency on longitude:

- The european sector is stronger affected than others.

Spread-F is dampened during:

- Geomagnetic sub-storms (induced by the Earth), pre-midnight sector more stable but post-midnight sector potentially more unstable.

Spread-F occurs within ~ ±15º latitude of the geomagnetic equator and between 400-1000 km altitude, primarily in the 20:00-23:00 local time interval, but also in the post midnight sector during high geomagnetic sub-storms.

3.3 Effect of Spread-F on radio links

Due to the plasma instabilities ionospheric bubbles are created. The effect on radio links are steep variations of the signal strength (scintillations). The phenomena are described in different papers, and the observations of the Cluster spacecraft fit quite well (Billig et al., 2003).

4 APPLICABILITY OF SPREAD-F TO OBSERVED LINK ANOMALIES

4.1 Cluster spacecraft

IGS TEC maps (Feltens, 2003) were used to find out whether the affected RF links passed through potential areas of Spread-F. For the majority of the reported anomalies this could be confirmed with the IGS TEC maps.

Figure 4-1 shows an example of AGC fluctuations on SC4, when being tracked on 17 October 2002 from Maspalomas. The duration of the SC4 pass was from 17:59 – 21:24 UT. Fluctuations were recorded from 19:45 UT until the end of the pass. The penetration points of the RF links with the ionospheric shell are marked with a black/white spot in the corresponding IGS TEC maps of Figure 4-1. The IGS TEC maps are given with a two-hours time resolution, in the case of Figure 4-1 at 19:00 and 21:00 UT. – So the white dot in the 21:00 IGS TEC (the right one of Figure 4-1) is obviously located in the suspicious region.

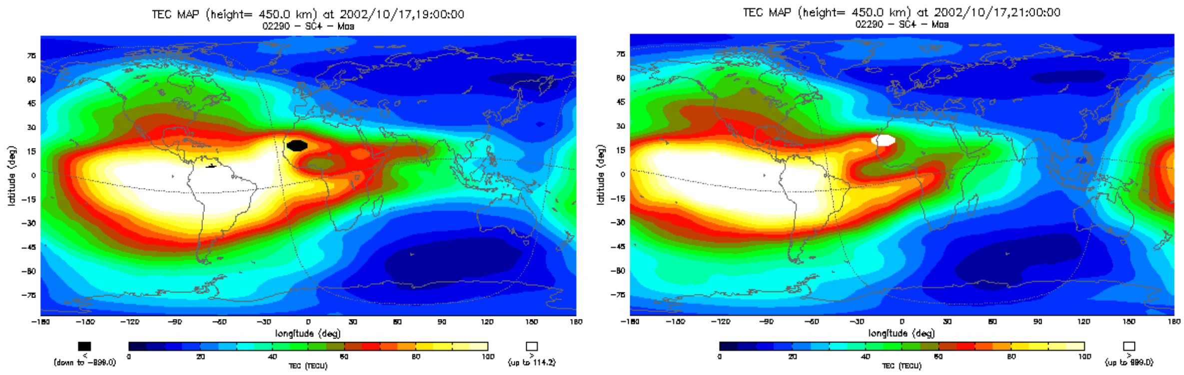

Figure 4-1: Penetration point of the RF link with the ionosphere, Cluster, 17/10/2002, with SC4 tracked from Maspalomas, courtesy IGS Iono WG.

Also passes were inspected where the Cluster spacecraft were operated in parallel with Maspalomas and Villafranca (similar longitude) and link anomalies were only observed at one of the stations (Maspalomas). In Figure 4-2 presents an example of such a case on 19 March 2003 (i.e. in winter, not in autumn): SC4 was tracked from Maspalomas, and from 20:40 – 21:00 UT fluctuations were observed on SC4. SC1, SC2 and SC3 were tracked from Villafranca with stable links. The penetration points of the RF links with the ionospheric shell are marked with a white spot in the corresponding IGS TEC map of Figure 4-2. It can clearly be recognized that in the case of SC4 (the right one in Figure 4-2) the intersection point marked with the white dot is located in the suspicious region of Spread-F appearance, while the intersection point of SC1 (the left one in Figure 4-2) is quite distant from that region.

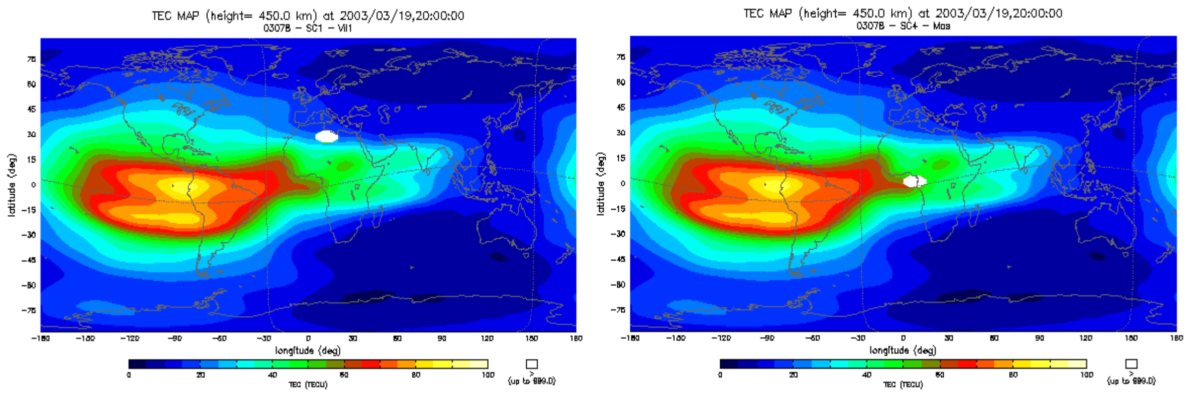

Figure 4-2: Penetration point of the RF link with the ionosphere, Cluster, 19/03/2003, SC1 (left) tracked from VIL and SC4 (right) tracked from MSP, anomalies were only observed on SC4, courtesy IGS Iono WG.

The fact that anomalies with Cluster were mostly observed during late autumn are due to the visibility of the spacecraft in the evening hours during that time of the year only (orbit plane inertially fixed, see Section 2.2.3 above). The Cluster apogees are positioned over the southern hemisphere, whereas the used ground stations are located on the northern hemisphere.

4.2 Other spacecraft

4.2.1 MSG-1

To further prove the theory, additional investigations were performed with other spacecraft, where similar effects had been observed. The penetration point of the RF link with the ionosphere is marked with a white spot in Figure 4-3. In this example AGC fluctuations were observed on MSG-1 on 6 October 2002, 21:00 – 22:30 UT, from Maspalomas (and again on 7 October 2002).

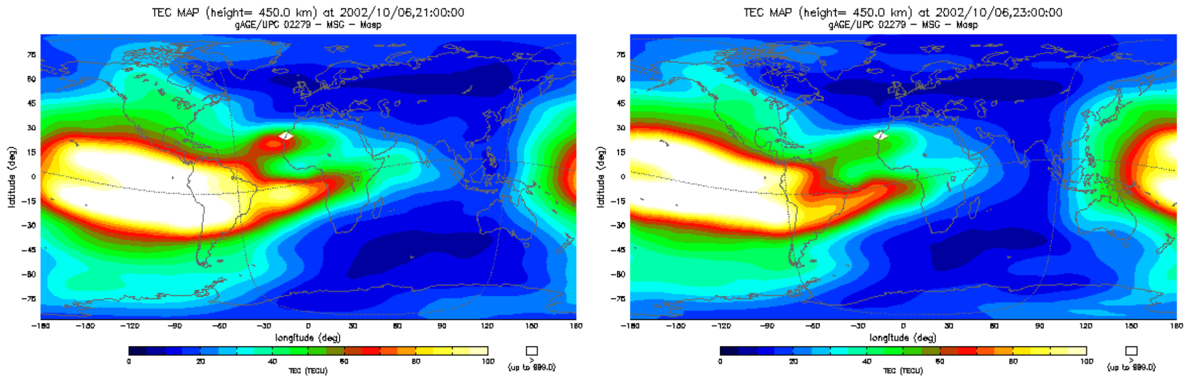

Figure 4-3: Penetration point of the RF link with the ionosphere, MSG-1 satellite, 06/10/2002, tracked from Maspalomas, courtesy IGS Iono WG.

The IGS TEC maps show that the penetration point of the RF link through the ionospheric shell is also in the critical area at the edge of the ionospheric cloud, where Spread-F can be expected. Again, Maspalomas was the tracking site.

4.2.2 XMM

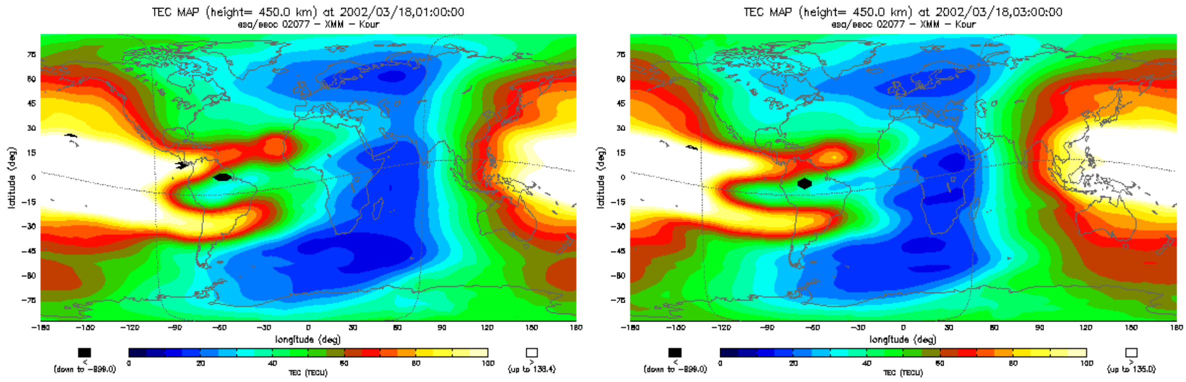

Figure 4-4: Penetration point of the RF link with the ionosphere, XMM satellite, 18/03/2002, tracked from Kourou, courtesy IGS Iono WG.

During XMM operations also RF link degradations were observed in March 2002. The Kourou ground site was used for these passes. Figure 4-4 clearly demonstrates that the RF waves pass (marked as black dots) an area with potential Spread-F. The RF link fluctuations in Figure 4-4 were registered when tracking XMM from Kourou on 18 March 2002, 01:30 – 02:30 UT (and again on 20 March 2002). **– So in summary IGS TEC maps seem to confirm that all RF link anomalies observed with the different spacecraft and ground stations described above show consistency and that the anomalies are linked to Spread-F.**

5 OPERATIONAL CONSEQUENCES FOR CLUSTER

There exist several possibilities for Cluster operations to handle the Spread-F problem, of which the most practicable are (Billig et al., 2003): 1) Usage of another nominal ground station than Maspalomas, e.g. Perth (conflicts with other missions), or allocation of a second antenna in Villafranca. 2) Change of the Cluster orbits to increase visibility at ground stations located on the northern hemisphere, i.e. reduction of the argument of perigee by 7 – 9 degrees during the constellation change manoeuvres in 2004, which is currently considered.

6 POSSIBLE CONSEQUENCES FOR FUTURE ESA SPACECRAFT AND MISSIONS

With regard to future spacecraft design, ground stations selection and operations to cope with the effects of Spread-F, recommendations were stated by the cross-disciplinary working group of experts at ESOC and ESTEC, some of these are (Billig et al., 2003): 1) If possible, frequencies of the X-band should be used. 2) If S-band has to be chosen as RF communications channel, mission analysis should take Spread-F phenomena into consideration. Ground stations where the RF path does not intersect with the potentially problematic areas of the ionosphere should be preferably selected. If equatorial station locations cannot be avoided, backup stations in different longitudes should be foreseen. 3) Parallel usage of two ground stations being differently located, if link anomalies are likely. 4) Sufficient time or dump rate margin and on-board storage capabilities should be foreseen to repeat data dumps, if necessary. 5) Spread-F impacts on navigation satellite systems, like Galileo, should be considered in the system design. These navigation satellites can also be used to observe the ionosphere.

Prior to Spread-F appearance, the ionospheric F-layer moves rapidly up (see Chapter 3). A permanently installed ionosonde at Maspalomas could be used to observe routinely the electron density profile above the station. An observed sharp raise of the F-layer height in the local evening hours would then be an indicator of increased Spread-F risk. To the Spacecraft Operations Manager one or two hours of time would be left for looking for an alternative tracking site. An installation of a permanent ionosonde at the Maspalomas station (and maybe also at other ESA tracking sites) is currently considered.

7 CONCLUSIONS

The Cluster spacecraft suffer from seasonal link degradations up to complete signal loss. A working group of experts from ESOC and ESTEC investigated the problem and could identify Spread-F as the source of the problem. Several proposals were made by the working group to handle the Spread-F phenomenon in routine operations of the Cluster spacecraft. Recommendations were formulated how to take care for Spread-F in future missions planning and design. The installation of ionosondes at selected ESA tracking sites as aiding tools to make Spread-F forecasts is currently considered

IGS TEC maps played a key role to relate Spread-F appearance to observed satellite link disturbances at Cluster and other spacecraft.

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