Operational Aspects of an Innovative, DVB-S based, Satellite Ranging Tool

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Introduction
Compared to classical TT&C tone ranging systems, the use of payload signals has tremendous advantages for the satellite operator. The payload based ranging signal is always present, so without dedicated activation, and without impact on the satellite control activities, a reliable and precise measurement is available. Classical tone ranging actually has to be activated by satellite commanding, and, depending on the satellite manufacturer, the telemetry stream is partially interrupted during a ranging campaign. For these reasons, tone ranging campaigns are limited in time, in contrary to payload methods, which provide continuous range data. Last but not least, the accuracy of payload ranging is in general superior, mainly due to the large bandwidth and high signal-to-noise ratio. The latter two effects also make payload ranging an optimal solution for orbit determination.

A first payload ranging implementation had used analogue FM modulated TV signals, which measured the delay of the video signal’s vertical synchronization pulse. In direct-to-home broadcasting, the DVB-S standard is used since its introduction on a growing number of transponders and satellites. In order to maintain the advantages of payload ranging on DVB-S operated satellites, SES ASTRA developed the new DARTS (Digital Advanced Ranging using Transport Stream Signal) in cooperation with the Fraunhofer Institute for Integrated Circuits.

The present paper starts with an overview of how DARTS devices work, focussing on the realisation of operational devices, and developments going beyond the prototype stage. The operation is explained in its most simple configuration, the single station ranging case, before addressing the more complex multi-station case. Before concluding, we explain the employed validation methods, assess the DARTS’ performance for different configurations, and compare it with classical ranging and orbit determination systems.

The DARTS Ranging devices
The first prototypes of DARTS ranging devices have been extensively tested in laboratory environment and on satellites. For details on these results and derived applications, see references [1] and [2]. As the prototype evaluation confirmed that the measurement algorithms were robust and mature, they were implemented almost unchanged in the operational system.
An overview of the operational DARTS device architecture is represented in figure 1, based on which we shortly explain the device functionality. The Test Data Generator injects the ranging packets with specifically attributed packet identifiers, via ASI interface into a multiplexer or a QPSK modulator of the uplink chain. The RF switch within the ranging receiver part provides a device calibration function. The QPSK modules generate analog IQ signals (demodulated L-band signal) and decoded MPEG transport streams to the IRD interface. The DSP module detects the decoded ranging packets and re-encodes the received transport stream part to a regenerated IQ signal. This data stream section is then correlated with high-precision-synchronously stored IQ samples and the exact packet arrival time is calculated as result. An external GPS receiver provides the time and frequency reference to time-tag the stored IQ samples and also serves to synchronize multiple DARTS receivers. The DRR (Dual Ranging Receiver) Controller is a PC software, which configures the device and collects the measurement data.

While the prototypes have been designed to evaluate the DARTS functionality and performance, the further developments to the operational system largely improved the user interface. The result is a compact device, with all hardware parts integrated, and with comprehensive connection interfaces. The keypad, the LED’s and the LCD graphics display provide an efficient representation of operating status information. Another important aspect is that an industrial manufacturer assures the operational devices production, including the performance of EMC tests on emission and robustness. Comprehensive test procedures are available for proof of functionality and measurement accuracy of the operational devices, which facilitates cost-efficient reproduction for further series. An operational device is shown in figure 2.
Operational Configurations: Single station ranging

The set-up of a single station, single satellite DARTS ranging system comprises different elements: the ranging packet generator, one ranging receiver (RR) input connected to the transmit path and a second ranging receiver input connected to the receive path of an antenna. As long as a payload uplink station is equipped with corresponding RF couplers, the only additional devices required are a test-loop translator and two block downconverters to convert the RF signals to L-band (see figure 3). According to the previous device description, the test data generator and both ranging receivers are integrated into a single device, nevertheless, a separate test data generator can also inject the packets into the multiplexer, as this might be more convenient in some cases.
The DARTS device determines the precise packet arrival time of each ranging packet at both ranging receivers. The connected monitor and control PC associates the corresponding packet arrival time values, calculates the round trip delay and converts this to the range value. To avoid ambiguity for associating a ranging packet at RR1 to a packet at RR2, each ranging packet is numbered. The M&C also connects to a central workstation gathering all ranging and AZEL measurement data. In case of a larger fleet, a multi-satellite configuration is achieved by simply adding multiple DARTS devices to at least one respective satellite payload uplink station. An interesting advantage of the chosen system architecture is that a single M&C PC can connect to multiple DARTS devices, thus a centralized operation and monitoring is achieved.

As opposed to other ranging systems, a regular station calibration is not required as the transmit couplers are located after the multiplexing and RF combination network. The latter part is subject to non-deterministic delay variations, whereas the upfront waveguides and antenna part introduce only deterministic delays. A one-time station calibration is thus sufficient.

The operational device’s performance remains identical to the prototype system’s, which has been described in [1]. For recapitulation, we represent the short-term measurement assessment in figure 4. Please note that we represent the accuracy of the device, the overall range measurement is furthermore influenced by long term effects, such as ionospheric and tropospheric refraction. In absolute terms, the satellite transponder delays are furthermore adding biases, if not precisely known.

![Figure 4: DARTS performance on satellite measured range](image)

**Operational Configurations: Multi station ranging**

For ranging a single satellite from different, geographically wide spread stations, the multi-lateration concept, comprising several identical stations performing active ranging, is well-known. Such a system, developed by SES ASTRA, called trilateration system henceforth, has been described in [4]. For DARTS multi-station ranging, we chose a slightly different approach, which consists of a single transmitting station per satellite, and multiple receive-only measurement stations.
We did not consider the trivial solution, which is to equip multiple uplink stations, located on different sites, for several reasons. An important aspect is that we want to limit the implementation of a ranging system to only a single payload uplink stations. Furthermore, remote payload uplink stations are located where a customer or a suitable teleport is, but the uplinks may not be located at favourable separations for orbit determination purposes. The best angular resolution in a multi-lateration system is achieved with the widest possible separation of ranging stations, which is at the edges of the footprint.

The proposed solution uses only a single uplink and multiple receive stations, whereas all stations have to be tightly synchronized and interconnected with data links as represented in figure 5. This solution is called pseudo-ranging, as the signal delay between a first station – the satellite – a second station is measured instead of simple round trip delay between a station and the satellite. At the uplink, a first ranging receiver (RR0) measures the ranging packets’ (RP) transmission time. Optionally, at the uplink site, we could also measure the RP arrival time; which is not represented here, but is identical to the single station configuration in the previous paragraph. At multiple remote sites, the receivers RR 1, 2, 3, … measure only the packet arrival time (PAT) of the RPs with respect to their own time and frequency reference. All data is transferred to the system controller (SC), which calculates the resulting pseudo-range out of the different packet time stamps collected in uplink and downlink sites.

![Figure 5: multi-station, pseudo-ranging](image)

The critical items in this configuration are

1. Reliability of GPS time synchronization between different sites
2. Synchronization between GPS device and ranging device
3. Calibration of uplink respectively downlink path separately
The time synchronization is performed with specialized GPS receivers, which achieve very tight time synchronization even under selective availability, and rely on an intelligent averaging of different GPS satellite measurements. In a lab configuration, two close by systems measured the time difference between 2 GPS receivers and the distance measurement of a short cable. The results of this experience showed that the ranging errors are mainly depending on the GPS time difference; details can be found in [2]. As soon as the systems are installed a few hundred kilometers apart, the direct GPS time comparison is no longer possible. The assessment for the deployed stations has been done using the active SES ASTRA trilateration system for the 19.2 East position (ref. [4]) as reference system. The experience shows that with a good reference satellite orbit, one can also precisely measure the time synchronization between remote stations.

Another important aspect is that besides the synchronization between GPS receivers at different locations, the connection between the GPS 10 MHz and 1 PPS references and the DARTS ranging device is of utmost importance. The design of the DARTS devices includes an algorithm providing a reproducible and foreseeable synchronization, as described in [2].

A last challenge for the described implementation is the calibration, which can no longer be performed as in a normal configuration, between the same device’s transmitter and receiver. The values of uplink path delays at the transmit station and the downlink at the receive-only stations have to be determined separately. One method to perform this calibration can be found in [3]. Another simple solution consists in using an auxiliary cable and a mixer to replace the uplink or downlink path in a simple ground calibration. Here, the uplink signal can be translated back into the receive band by the mixer, which remains the only (negligible) unknown delay.

**Orbit determination performance**

The purpose of this chapter is to outline some aspects of the pseudo ranging system accuracy. Following pseudo-ranging system configuration (figure 6) has been evaluated:

- Uplink station in Betzdorf (Luxembourg),
- One downlink station in Sevilla (Spain) and one in Bergen (Norway).

These two downlink stations were in fact located close to the already existing slave ranging stations.

Here are the hypothesis used for the pseudo-ranging system evaluation:

- Availability of the pseudo-ranging system calibration values (uplink, downlink and satellite delays)
- Accurate position coordinates of the uplink and downlink stations (within 5 m)
In order to illustrate its accuracy, the pseudo-ranging system has been compared to following two common tracking systems:

- **Multi-station configuration**, using three two-way range measurements:
  - Betzdorf → Satellite → Betzdorf
  - Sevilla → Satellite → Sevilla
  - Bergen → Satellite → Bergen

- **Single station configuration**, using
  - Two-way tone range measurements: Betzdorf → Satellite → Betzdorf
  - Azimuth and elevation from a mono-pulse antenna located in Betzdorf

As reference system to support the comparison of the different tracking systems, the trilateration system used by SES ASTRA to co-locate a large number of geo-stationary satellites (up to 8 in 1998, see [5]) at 19.2 East has been used. This very accurate system is currently composed of a master ranging station located in Betzdorf and of three so-called slave ranging stations located in Sevilla, Fucino and Bergen. The accuracy of the trilateration system has been extensively discussed in the reference papers [4] and [5] and is mainly driven by the spatial separation of the ground stations.

- The evaluation of each tracking system accuracy has been performed as follows: For each tracking system, seven orbit determinations have been performed and each determination was based on two complete days of tracking data.
- The orbit determination results have then been compared to a best known reference orbit determined using the trilateration system
- The maximum resulting position errors over a propagation of 7 days along the normal, radial and tangential directions (spacecraft local frame) have then been determined.
Table 1: Tracking system Accuracy Evaluation – Maximum position error over 7 days orbit propagation along the normal, radial and tangential directions (spacecraft local frame)

<table>
<thead>
<tr>
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<th>MULTI Station (Distance)</th>
<th>PSEUDO-Ranging (Distance)</th>
<th>Single Station (Tone distance + Angles)</th>
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<tr>
<td></td>
<td>Betzdorf</td>
<td>Betzdorf-&gt;Sevilla</td>
<td>Betzdorf</td>
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<td></td>
<td>Sevilla</td>
<td>Betzdorf-&gt;Bergen</td>
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<td>Mean [m]</td>
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<tr>
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<tr>
<td>Std [m]</td>
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<td>84.0</td>
<td>251.0</td>
</tr>
</tbody>
</table>

The accuracy results shown in Table 1 are now briefly commented:

- **Single-station configuration:**
  The large normal component error results directly from the low accuracy of the antenna elevation measurements. The satellite position accuracy strongly depends on the relative position of the satellite location on the geo-stationary arc and of the ground station location, which determines the observability of certain orbit determination parameters. With a longitude separation of 13 deg between the satellite sub-longitude and the ground station, the ranging measurements, which are more accurate than the azimuth measurements, drive basically the position accuracy along the radial and tangential directions. Note that this single station configuration is the baseline configuration in case a satellite anomaly causes a payload switch-off.

- **Multi-station and Pseudo range system:**
  Contrary to the normal and radial position error, the tangential position error builds up over time. Table 1 shows that both the multi-station and pseudo-ranging systems provide a significant accuracy improvement compared to the single station along the radial and normal directions. By ensuring a separation along these two directions, the eccentricity and inclination separation strategy (see ref. [5]) used to co-locate a large number of satellites at one orbital position takes directly advantage of the high accuracy of the two systems along the radial and normal directions. The rather good accuracy of the pseudo-ranging system along the radial and normal separation would support therefore a safe co-location of a large number of satellites.
The following two figures show examples of residuals (difference between estimated and predicted measurements) plot for tone ranging in the single-station configuration Figure 7 and in the Pseudo-range system Figure 8. It can be seen that the range residuals variation remains within 10 m over a tracking interval of more than one week.

Figure 7: Residuals for tone-ranging in single station configuration

Figure 8: Residuals for pseudo-ranging system
Conclusion

The first experiences with DARTS confirm the expected advantages of a payload based ranging system, as there are: decoupled operation from satellite commanding, high accuracy and continuous ranging data availability. The clear separation of tasks between the DARTS hardware and M&C software allows an efficient and centralized operation, configuration and maintenance.

SES ASTRA’s long term experience with dense co-location and the use of highly accurate reference ranging and orbit determination tools allowed a detailed and reliable assessment of the newly developed techniques.

The presented results confirm that the DARTS system configuration can be easily adapted to different requirements be it as prime or backup system, whereas trade-offs can be made between system complexity and orbit determination accuracy requirements. For instance, the multi-station configuration can be well used as orbit determination tool for a dense co-location. With inexpensive and quickly deployable remote slave stations, and a single ranging device in the uplink path for each satellite, a cost-efficient and accurate solution is given. No large and costly mono-pulse tracking antenna is required. The single station ranging can be well used to replace tone-ranging campaigns for on-station operation, and reduce considerably the operational efforts related to commanding tone-ranging.

Apart from the usage in SES ASTRA’s particular environment, operating seven co-located satellites at 19.2E, 3 co-located birds at 28.2, and single satellites at 24.2 E and 5.2 E, the system can be easily adapted to any other operator’s requirements.

References


