Measurements of Mechanical Disturbances of Vehicle Mounted, Mobile Very Small Aperture Terminals (VSAT)

Mario Lorenz, Markus Mehnert and Albert Heuberger
Fraunhofer IIS
Project Group
Wireless Distribution Systems/
Digital Broadcasting
Helmholtzplatz 2
D-98693 Ilmenau, Germany
{mario.lorenz, markus.mehnert, albert.heuberger}@iis.fraunhofer.de

Abstract

In this paper we present the results of a measurement of the applicable mechanical disturbances for Satcom–On–The–Move antennas in different driving scenarios. In particular, angular velocities and accelerations are considered. The measurement data is analyzed in both time and frequency domain to derive typical requirements for the design of tracking antenna systems. It is further shown that on this data, lowpass filtering before deriving the required accelerations causes only an insignificant error in the pointing angle, but has significant effect on the required accelerations.

Keywords

mobile VSAT, Tracking Antenna, Satcom–On–The–Move

INTRODUCTION

Both broadcasting and interactive two–way satellite services require increasing data rates. With nearly filled up frequencies below or in Ku–band (12...14 GHz), future growth can be expected in higher frequency bands, like Ka-band (20...30 GHz) and above. The need for higher data rates and the free space loss incurred at these frequencies will require high antenna gain, and thus highly directive antennas. Another affecting factor is frequency reuse by space–division multiple access, i.e. the usage of the same frequency by neighbouring satellites. Therefore, small antenna beamwidth is a key technology to facilitate the efficient usage of scarce ressources.

The smaller the beamwidth, the more difficult it is to point such an antenna into the right direction, that is, towards the correct satellite. This is particularly a problem in the mobile case. A bidirectional SOTM (Satcom–On–The–Move) system handling high throughput data communications must employ a Pointing and Tracking Subsystem to keep the antenna alignment within very strict limits (see [1]), even while experiencing adverse road conditions.

Antenna depointing beyond these limits would not only cause an outage of one's own service, but also actively interfere with services on neighbouring satellites. It is thus often a regulatory minimum requirement that the terminal must cease transmission if detects that certain off–axis–angle thresholds are exceeded (see eg. [2]).

Developing steerable, tracking antennas for vehicle mounted, mobile Very–Small–Aperture–Terminals (VSAT) in satellite communications requires detailed knowledge of the level of the mechanical disturbances that can be expected when driving different vehicles on different terrain. Examples for angular velocities and accelerations can be found in the scientific literature [3], in normative standards [4], as well as in various product literatures (e.g. [5], [6]). None of the available sources provided any detailed guidance on whether these figures were applicable to our particular vehicles or road conditions. Also, these sources did not give any information whether and how different frequency ranges of the disturbances were taken into account. It was therefore necessary to conduct our own measurements.

This report is organized as follows: First, we briefly describe the project for which the measurements were made. We then cover some definitions and mathematical background for the task. Afterwards we present our hypothesis. We then discuss our measurements, including the measurement setup and show actual results. Finally, we summarize the work and present our conclusions.

OBJECTIVE

The MoSaKa Project

The MoSaKa project (Mobile Satellite Communications in the Ka Band, [7]) is mainly concerned with communication amongst first responders and helpers in disaster relief scenarios. Of particular interest for our studies are therefore the requirements organizations like fire brigades or the german THW (Technisches Hilfswerk, German Federal Agency for Technical Relief) may have. These requirements include nomadic high throughput setups with quick and precise automatic antenna alignment[1]. Also included are Satcom–On–The–Move scenarios, where pointing and tracking during movement is required.

BACKGROUND

Vehicle Motion

We assume that the rules of rigid body physics apply, both for the antenna as well as for the vehicle. Also it is assumed that the antenna will not be sensitive to direct wind load. This is reasonable, since it usually will be protected by a radome. Assuming further that the satellite is fixed (i.e., geostationary), the main — if not the only — source of force to drive an antenna off–axis will be the vehicle motion.

This motion consists of two classes. Linear (translational) motion affects the position of the terminal. It will not have much effect on the pointing angle of the antenna towards

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[1] While these organizations generally do have very knowledgeable and capable members, they often form small teams, so the SatCom expert will usually not be onsite.

the satellite, since the relative distance is usually small compared to the distance to the satellite. For purposes of this work, we therefore neglect it.

The main focus of this work is the second class of the vehicle motions — rotational motion. It may occur in any axis and motion will affect the orientation, or attitude, of the vehicle. Since the antenna is mounted to the vehicle, its look angle towards the satellite will change. In order to keep the antenna aligned, it will thus be necessary to compensate for the effects of the vehicular motion and adjust the antenna pointing angles.

Vehicle Attitude

The attitude of the vehicle relative to the local tangential plane (LTP) can be described using the Cardan[2] angles yaw (ψ), pitch (θ) and roll (ϕ). Yaw pertains to the azimuth angle of the vehicle, rotating around the vertical (Z) axis. Pitch, sometimes also called nick or inclination angle, is the rotation around the lateral (Y) axis of the vehicle. Roll, finally, is the rotation around the longitudinal (X) axis.

Satellite position

The position of a geostationary satellite is commonly given as azimuth and elevation angles, relative to the same location, and thus the same LTP. If the satellite is not geostationary, these angles are time variant.

For purposes of our work, we used a fixed satellite position of 180 degrees azimuth (i.e. south) and 60 degrees elevation. This rather high elevation was choosen to provide sufficient margin when operating the antenna in other geographical areas.

Pointing angles

An antenna positioner mounted on a vehicle needs the satellite position relative to the vehicle, not to the LTP. These angles are commonly called look or pointing angles. Although not necessarily aligned to the horizon, these angles (and their respective positioner axes) are often also called ”Azimuth” and ”Elevation”. Care must be taken to distinguish Pointing/Look angle Azimuth/Elevation and true (LTP) Azimuth and elevation angles.

They can be calculated[3] by transforming the satellite coordinates from the LTP frame into the vehicle body frame, using Eq. 1

$$r^b = C_L^b r^L \tag{1}$$

where r^L is the vector of the satellite in the LTP frame (also often called n–(Navigation–)frame) and C_L^b is the direction cosine matrix of the vehicle, given by [8] as

$$C_L^b = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{pmatrix} \cdot \begin{pmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{pmatrix} \cdot \begin{pmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

The designer for a tracking system will be mostly concerned with these pointing angles and their time derivatives, angular velocity and angular acceleration, to determine the capabilities (ranges) the antenna positioner must have.

Pointing Angle range

It is obvious that in order to cover all possible (and likely) vehicle attitudes, substantially all of the hemisphere has to be reachable by moving antenna pointing azimuth or elevation. However, a special region is the so called keyhole region at the zenith. Many two–axis designs will not reasonably work in this region, since the pointing elevation approaching 90 ° results in highly increased angular acceleration requirements [9] and ultimately the loss of a degree of freedom. This condition is called gimbal lock. If performance near the zenith is required, special measures like an additional axis must be taken. Unfortunately, this will significantly drive up cost and complexity of the system. In some special cases (low satellite elevation, hilly terrain), the capability to reach out to negative elevation angles might be useful. In these cases, satellite visibility is however often limited by the vehicle roof.

Angular Velocity and Acceleration

The main parameters of interest are the dynamic parameters of (angular) velocity and acceleration. Ultimately, they define the required torque, which in turn defines the size, weight and power requirements of the antenna positioner.

Angular velocity is the first time derivative of the angle:

$$\omega = \frac{d\beta}{dt} \tag{3}$$

(Angular) acceleration is it’s second time derivative:

$$\alpha = \frac{d\omega}{dt} = \frac{d^2\beta}{dt^2} \tag{4}$$

HYPOTHESIS

Acceleration and velocity do not tell anything about the frequency of the disturbance. The disturbance might be low freqency up- and downhill driving on an otherwise good road, or, on the other hand, high frequency vibration, caused by the engine of the vehicle. They would have different effect on the antenna pointing.

We assume a sinusoidal angular disturbance (e.g. like a torsion balance in a watch) β_d of a frequency ω_d and amplitude a_d

$$\beta_d = a_d \sin(\omega_d t) \tag{5}$$

To cancel this disturbance, a motion of

$$\beta_{comp} = -a_d \sin(\omega_d t) \tag{6}$$

must be added. The required acceleration α_d can then be computed using (4):

$$\alpha_{comp} = \frac{d^2\beta_{comp}}{dt^2} = a_d \omega_d^2 \sin(\omega_d t) \tag{7}$$

As can be seen, the required acceleration to cancel a given disturbance increases with the square of it’s frequency.

Put in another way, trying to compensate a high frequency disturbance by expending the necessary high acceleration would be in vain, since the effect of this disturbance on the

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[2] These angles are also often called Euler angles, but this is ambiguous. Cardan angles are commonly understood to use the rotation convention described above, whereas the ”Euler angles” that are popular in physics use a different rotation sequence.

[3] Wheter these look angles are eqivalent to the axis angles depends on the construction of the positioner. If a different construction is prefered, the calculations must be modified.

look angle diminishes with rising frequency, up to a point where it may be ignored.

Looking only at discrete frequencies is a somewhat simplicistic approach, since a real disturbance will consist of a spectrum of frequencies. This hypothesis essentially ignores phase and crest factor, where several small amplitude components might add up unfavourably. In our measurements however, this was not an issue.

MEASUREMENTS

Vehicles

With the help of THW, a series of measurements have been performed with various vehicles which were driven on a test track. At hand were three vehicles. The Mercedes G class offroader and the IVECO EuroCargo truck were both offroad capable. Furthermore, a NEOPLAN city bus was available (Fig. 1) This vehicle is however not designed for anything but paved road, and therefore was not capable of completing the whole test track.

Figure 1: This NEOPLAN bus is used by the THW as a mobile command center. It is therefore a prime candidate to be outfitted with Satcom equipment.

Test Track

The test track included a former army practice ground and consisted of different road conditions, ranging from highways and paved asphalt road in perfect condition to gavel roads in various states of disrepair, light offroad scenarios and scenarios judged to be very harsh offroad conditions. Artifical mounds provided examples of extreme tilt.

Based on interviews with THW personnel, it is very difficult to forecast the prevailing road conditions for the deployment area. These may range from excellent paved road to heavily damaged or non-existant roads, depending on the nature of the disaster. This has implications for the representativeness of the collected data. The data can not be used to model the distribution of the various road conditions to be expected during a real situation. It was however judged that the test track included all conditions likely to occur. Therefore, the data is valid to estimate worst–case or near worst case parameters, upon which the design of the pointing and tracking system ultimately would have to depend.

Both the test track route and the velocities used to drive on were choosen by THW drivers with the objective to cover a range of likely scenarios and drive at realistic (if not highest possible) speed.

Figure 2: IVECO EuroCargo Truck on artifical mound, during measurement.

Measurement Setup

Our measurement setup consisted of a high precision inertial measurement unit (Genesys ADMA), which contains fiber optic gyros and accelerometers. It is capable of measuring angular velocities and linear accelerations. By fusing them together with the DGPS (Differential GPS) signal, the unit will deliver precise estimates for location and attitude as well as their time derivatives, i.e. (angular) speed and accelerations. The estimated position error was in the centimeter range, and the tilt error estimates were below 0.1 degrees.

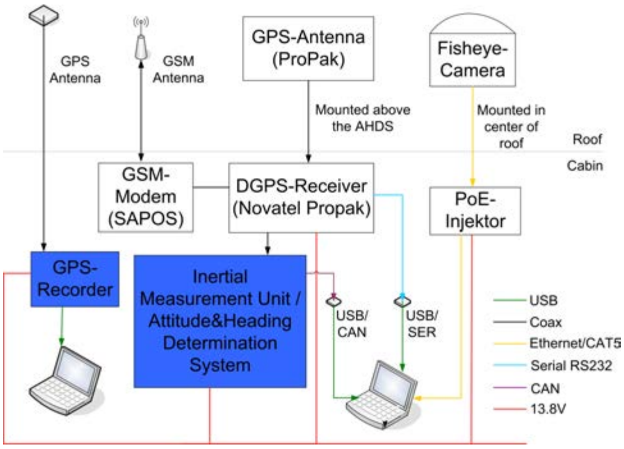

Figure 3: Measurement setup. The main instrument is a DGPS aided inertial measurement system, auxillary instruments were a GPS recorder and a hemispheric camera.

The data was recorded at 200 Samples/sec. The resulting data rate was too high for standard RS232 communication, therefore the data transfer was done via a CAN (Controller Area Network) interface at 1 MBit/s. The data was collected using a common laptop running Windows XP. A CAN/USB Interface was used to adapt the CAN signals to the laptop. A custom written logging application receives the CAN data and logs it as a CSV file, which can then be analyzed using standard tools like Matlab. Furthermore, the measurement system included a hemispheric (fisheye) camera to record the environment for later reference and a GPS recorder. The recorded data will be useful later when we plan to recreate the exact environment in our satellite communications testbed (see [7]).

RESULTS

The directly measured results from the test runs are angular velocities and accelerations of the vehicle in the vehicle body fixed coordinate system. After that, the measurement system computes absolute position and attitude information and transforms them into LTP coordinates. This data can then be plotted in the time domain.

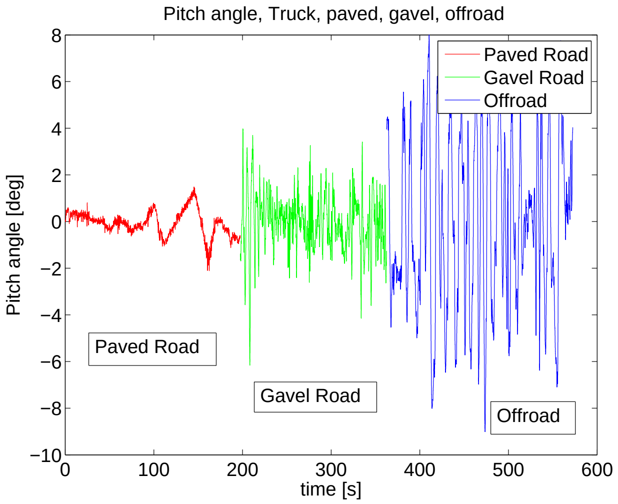

Figure 4: Pitch angle, Truck, different roads. The different angular dynamics are clearly visible.

Fig. 4 shows the pitch angle of the truck, on paved road, gavel road and in difficult terrain ("offroad")[4]. The difference of the various road environments is clearly visible. The plot for other vehicles looks very similar, differences would be caused only by the suspension systems and slightly deviating velocities.

Also note that, as expected, especially on the paved road the observed disturbances are small in amplitude, so that only minimal correction by the tracking system would be required. This is not the case in either offroad or gavel road cases, where up to ± 10 degrees of elevation change would be necessary.

After computing the look angles using (2), one would now double–differentiate this data to obtain the accelerations required to compensate this motion. The result is shown in Fig. 5. This figure shows a percentile plot of the look angle azimuth acceleration, across the whole dataset (ie. all vehicles, all tracks).

The graph shows that already in 50 % of the cases, supposedly an acceleration of about $250\,^\circ/s^2$ applies. This is unrealistically high. Unfortunately, the measured signal and in particular the computed angles include not only high frequency disturbances, but also quantization and/or rounding errors.

Drawing similar graphs based on single differentiation of the raw angular velocities as recorded, no such drastic distribution was observed. It must therefore be concluded that the angle data as computed by the measurement unit is too noisy to be (double-)differentiated without first being filtered. The spectrogram of this data, as shown in Fig. 6 however shows that not only noise components, but also vehicle vibrations are present.

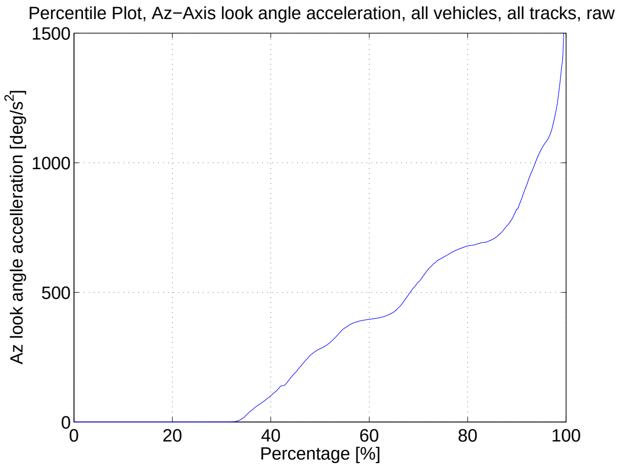

Figure 5: Percentile plot over the angular accelerations on the Azimuth axis, over the whole measured dataset (all vehicles, on all roads).

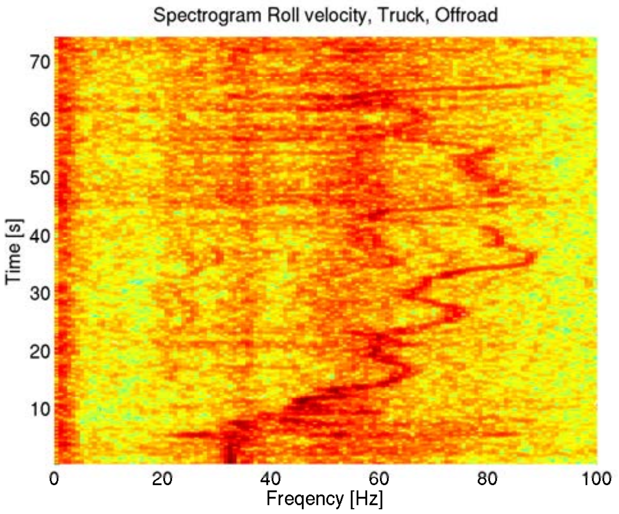

Figure 6: Spectrogram of Truck pitch acceleration (from raw measurement). The red curve betwen 30 and 80 Hz shows vibration caused by the vehicle engine at different rpm.

We filtered our data set with a lowpass filter (100th order FIR). The resulting error (i.e., the difference between the filtered and the unfiltered signal) are shown in Fig. 7 The cutoff frequency of 8 Hz was determined empirically so that an error of less than 0.1 degrees is caused in 99.7 percent of the time. It can be adjusted to different requirements. This shows our hypothesis to be correct, namely that frequency components of — in our particular case 8 Hz — in the compensation acceleration signal have only neglible effect, and may be filtered (they do not need to be generated or applied). Also, this filtering will reduce the noise effects.

Repeating the analysis (i.e., look angle calculation, differentation and percentile plots) using the filtered data, we arrive at the results shown in Fig. 8.

It can be clearly seen that the required acceleration (and therefore motor torque) is much lower than in the unfiltered case. The 99.7 % mark translates into an acceleration requirement of only $220\,^\circ/s^2$, compared to the original $1650\,^\circ/s^2$.

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[4] Data for the NEOPLAN bus is not available for all of these terrains

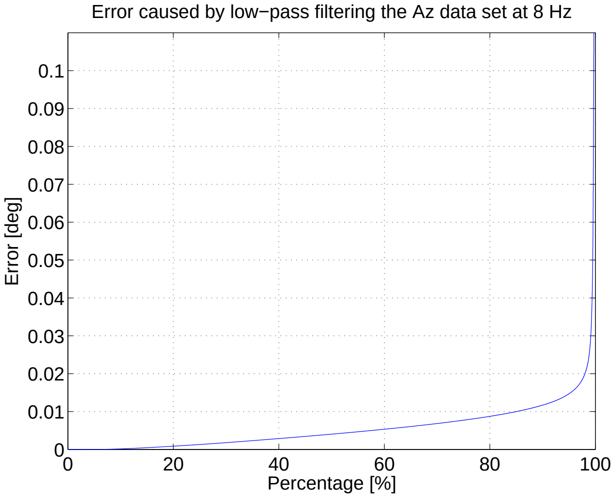

Figure 7: Absolute error between unfiltered and filtered signal, as a percentile plot. The error caused by filtering is neglible most of the time.

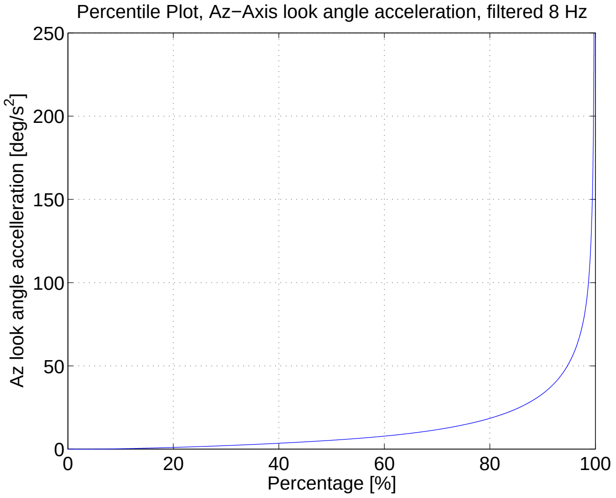

Figure 8: Accelerations, computed from look angles after filtering with an 8 Hz Lowpass filter (100th order FIR). Compared to Fig. 5, the required acceleration is much lower.

SUMMARY AND CONCLUSIONS

The dynamic requirements for pointing a VSAT antennas in Satcom–On–The–Move applications in disaster relief scenarios have been studied in a series of measurements. While the sampled data is not based on real missions and therefore does not represent entirely correct statistics, requirements for Near-Worst-Case scenarios can still be established. It was further shown that on this data, lowpass filtering before deriving the required accelerations causes only an insignificant error in the pointing angle, but has significant effect on the required accelerations.

It is envisioned that this work will be used to help design and build Satcom–On–The–Move terminals, for a variety of purposes.

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