K-Band Operations Study

Final Presentation

ESOC, Darmstadt
07 November 2012

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Contents

- Main tasks and objectives
- Simulation model
- Atmospheric attenuation models (statistical, time series)
- Link parameters and system noise contributors
- VCM and DLP strategies
- Site and time diversity
- Outage statistics
- Impact of timeliness requirement
- Optimum link operation concepts
- Protocols

Main Tasks and Objectives

- Identify and quantify signal fading contributions in K/Ka-Band
- Identify optimum link operation concepts for
  - highest yearly data volume
  - highest data volume given a maximum permissible yearly/monthly percentage of permanent data loss
  - highest data volume given a maximum permissible yearly/monthly average percentage of data not delivered within timeliness range
- Assume Ganymede, Mercury, L2, and moon rover scenarios
- Provide outage statistics
- Make recommendations for data retransmission strategies

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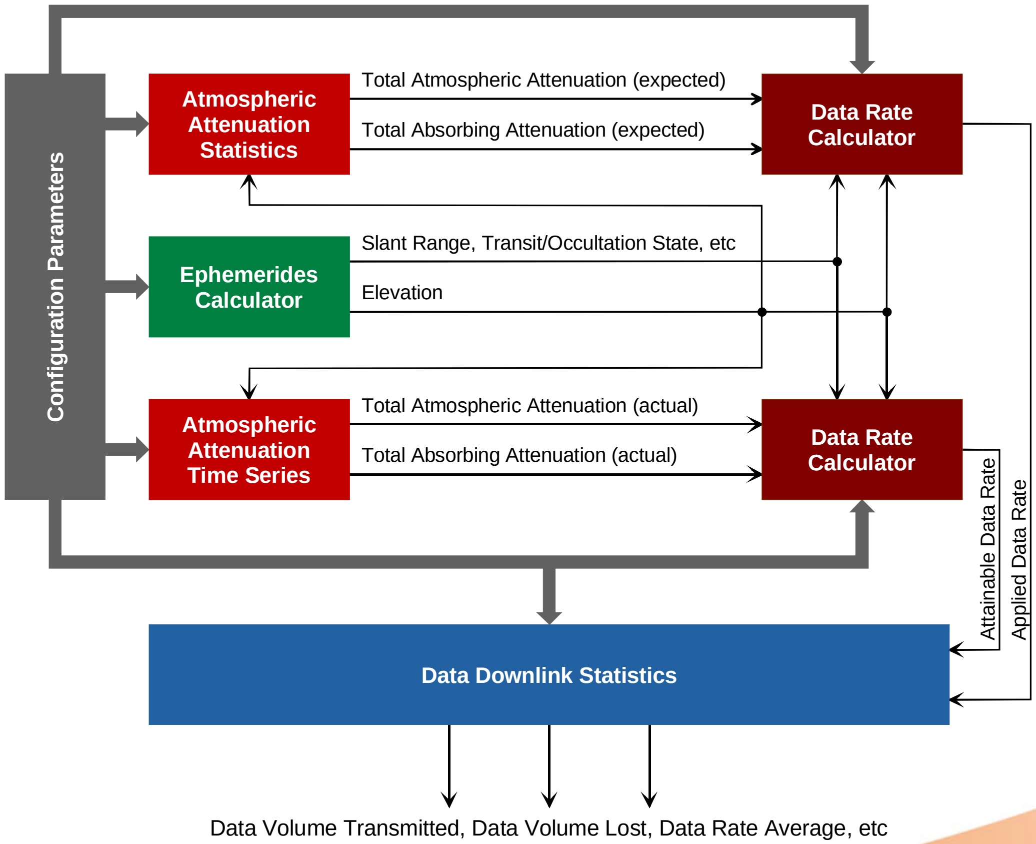
Simulation Model (1)



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Simulation Model (2)

- Taking into account the expected atmospheric attenuation (statistical value), ephemerides, various noise temperatures, link margin etc, the model determines the appropriate downlink data rate (applied data rate).

- In a parallel branch, the model generates an attenuation time series considering the coordinates of the observer and the current elevation.

- Taking into account the actual atmospheric attenuation (time series), the current ephemerides, various noise temperatures, and further parameters the model determines the maximum feasible downlink data rate (attainable data rate).

- At each time step the applied and the attainable data rate are compared:
  - applied data rate exceeds the attainable one $\Rightarrow$ complete data loss during period
  - otherwise $\Rightarrow$ no data loss and no bit errors during period

- A variety of parameters like data volume transmitted, data volume lost, average data rates, etc are provided by the model.

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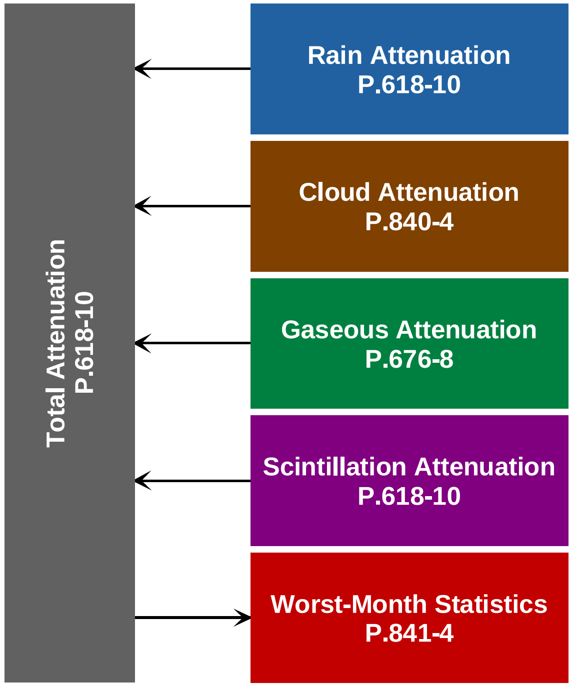
Atmospheric Attenuation Model
Statistical Model (1)

- Computation of long-term atmospheric attenuations based on the ITU-R recommendations of the P series.
- Considering statistical effects of rain, clouds, oxygen, water vapour, and scintillation on space-to-earth paths.
- Model also implements P.841-4 that permits to convert long-term into worst-month total atmospheric attenuations.



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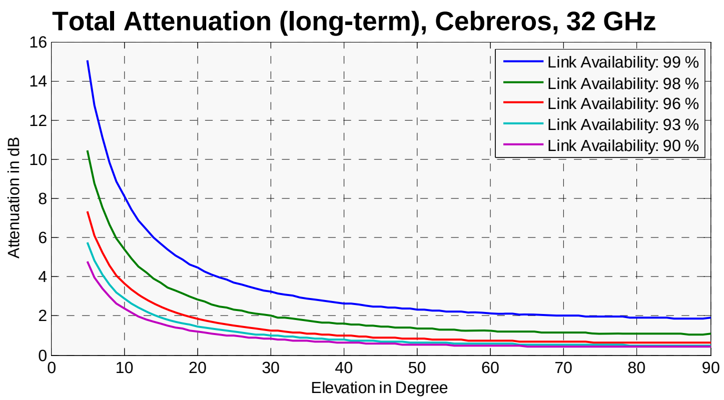
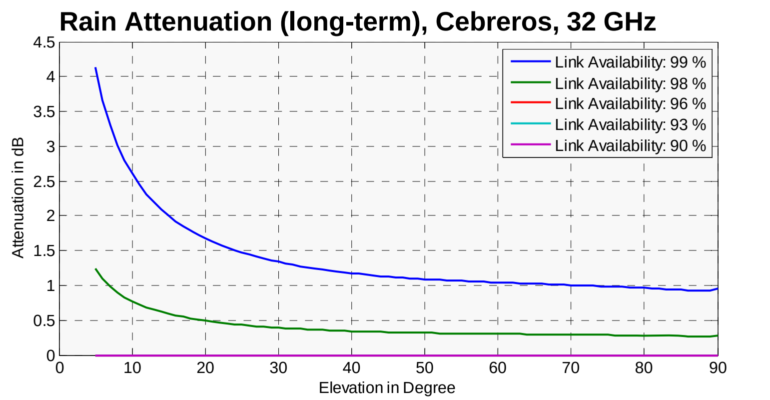
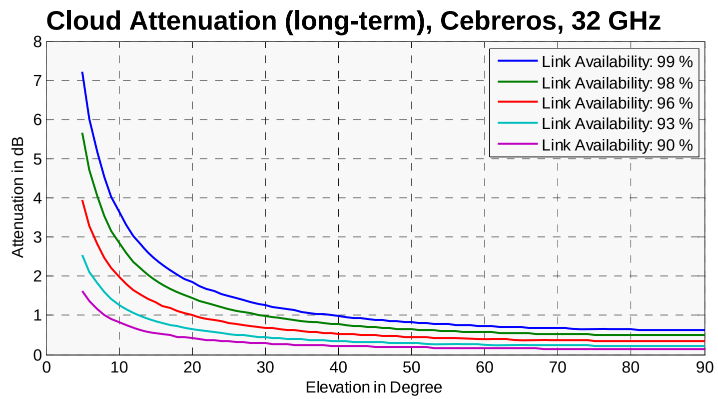
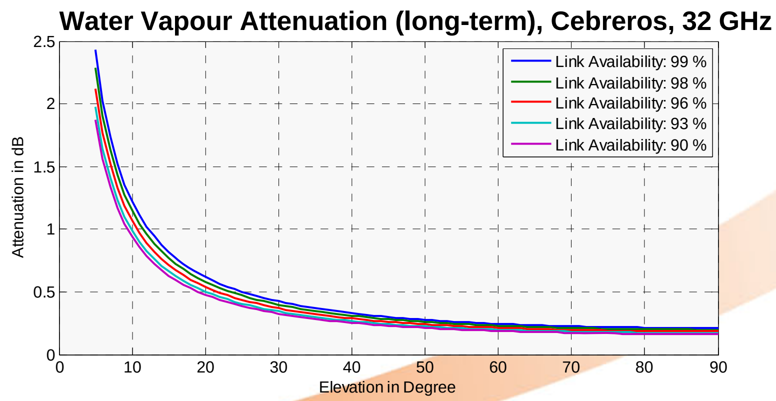
Atmospheric Attenuation Model
Statistical Model (2)









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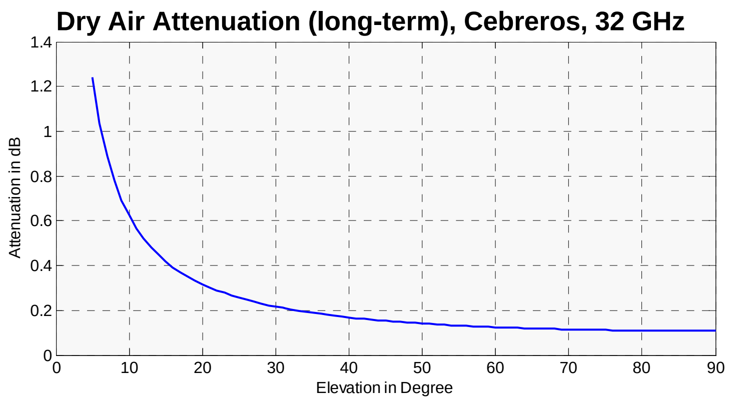
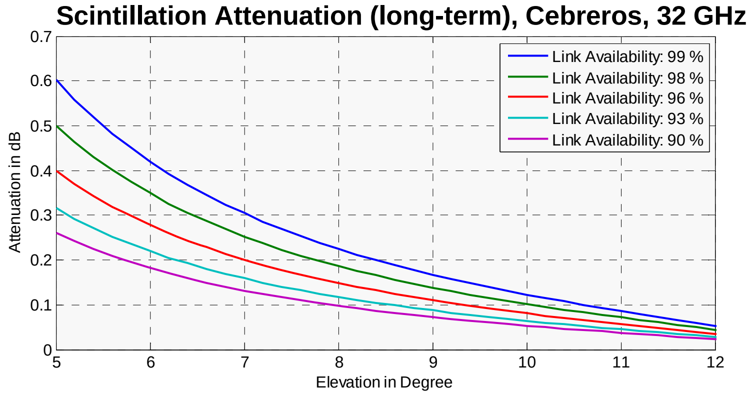
Atmospheric Attenuation Model
Statistical Model (3)





- Cloud attenuation is main contributor to total attenuation at low elevations.
- Rain attenuation is significant at link availabilities exceeding 100 % minus rain probability.
- Substantial contribution of gaseous attenuation at low elevations.
- Scintillation attenuation is negligible due to favourable combination of wavelength (short) and aperture area (large).

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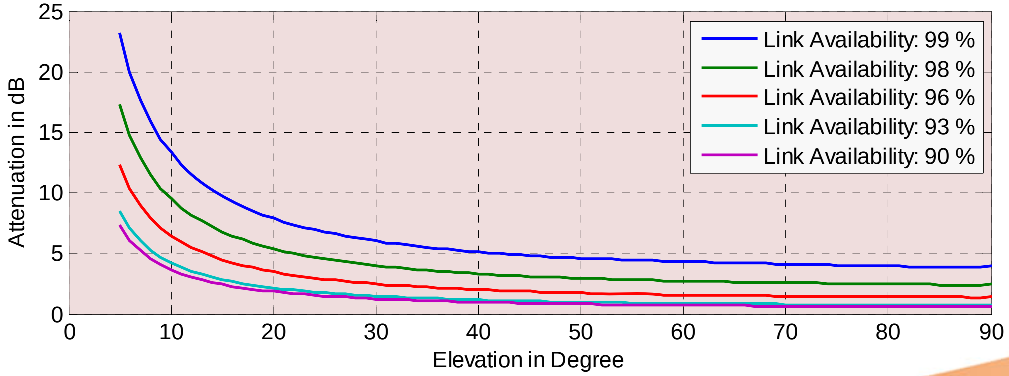
Atmospheric Attenuation Model
Statistical Model (4)

- Worst-month attenuation is derived from long-term attenuation.
- Conversion depends on character of geographical region:
  - dry region (e.g. dessert)
  - wet region (e.g. tropics)
  - global region (no specific character)
- Dry regions show higher degradation than the remainder, but on the basis of lower long-term attenuation.
- Plot below illustrates worst-month total attenuation in Cebreros at 32 GHz assuming global region.



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Atmospheric Attenuation Model
Time Series Model (1)

- The times series model uses to a large extent the same input data as the statistical model.
- The time series model generates samples emulating the attenuation due to clouds, rain, water vapour, dry air (oxygen), and scintillation (rapid fading).
- At each time step, the post-processor combines the individual components to create a sample representing the total atmospheric attenuation.
- The time resolution is one second which does not necessarily reflect the dynamics of all attenuation components involved.
- Scintillation exhibits a dynamics comparable to the time step size, whereas the processes describing water vapour and oxygen attenuation are extremely slow or even static. The dynamics of the remainder ranks between those extremes.
- The attenuation time series is synthesized in accordance with the model described in P.1853 (November 2011) extended by a worst-month conversion algorithm.

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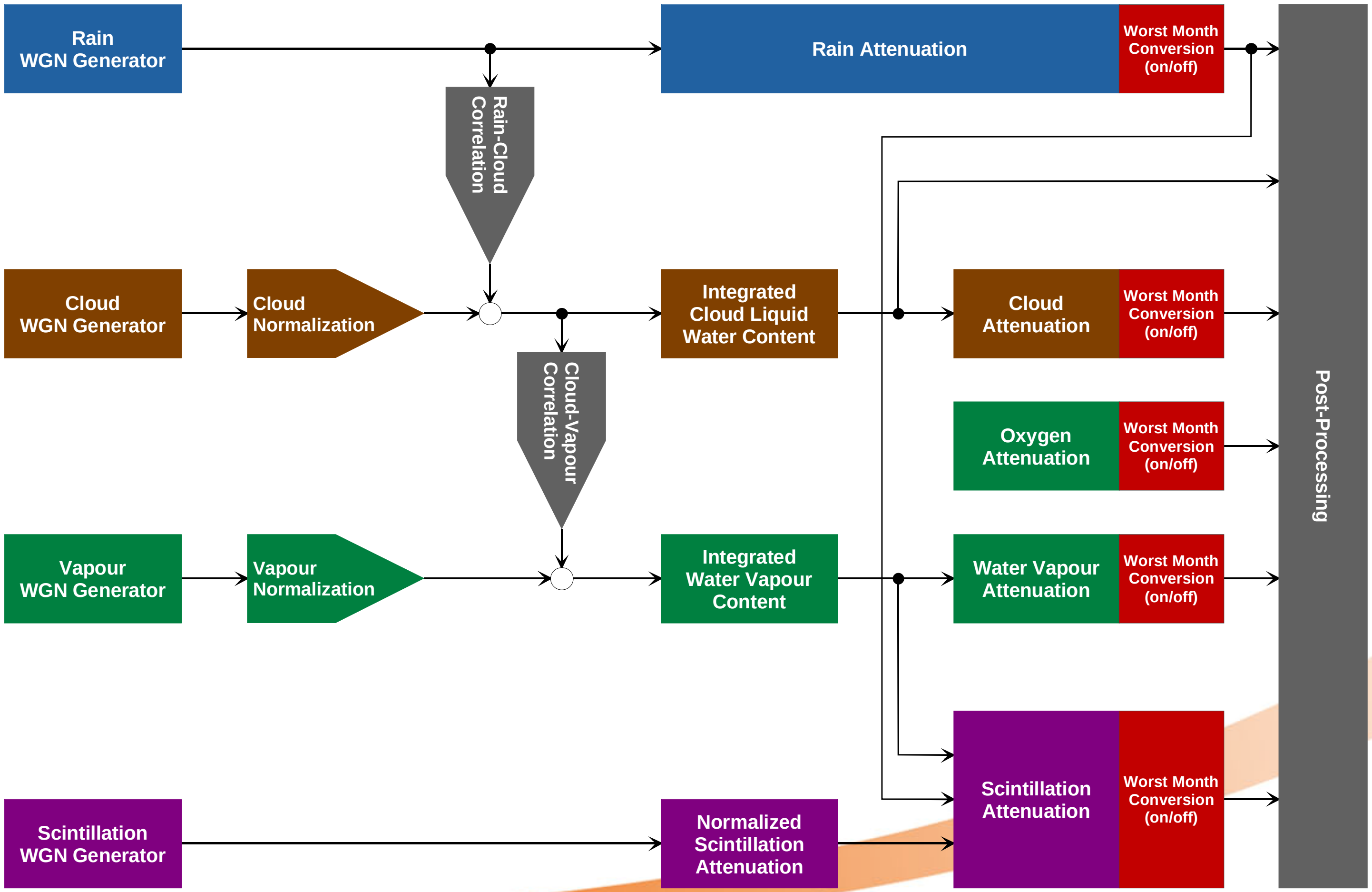
Atmospheric Attenuation Model
Time Series Model (2)



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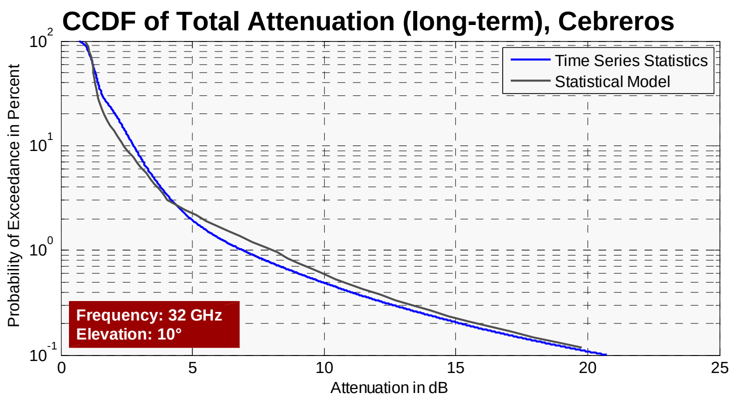
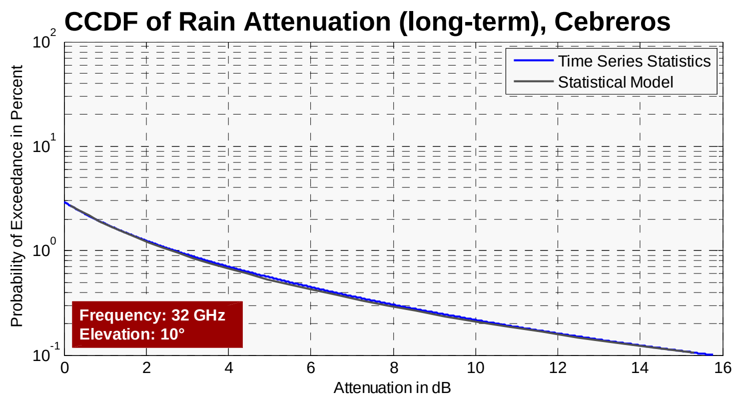
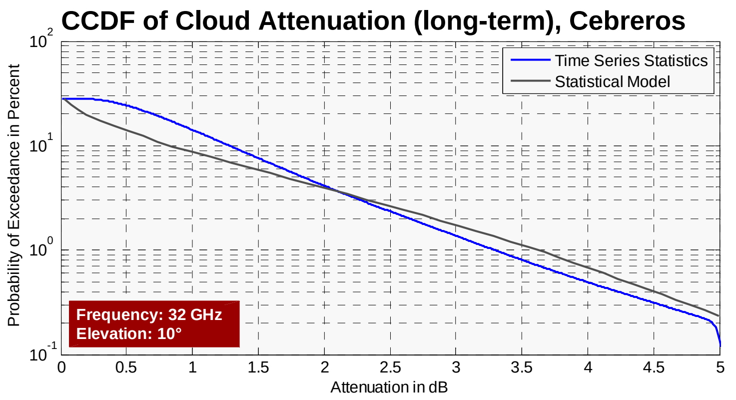
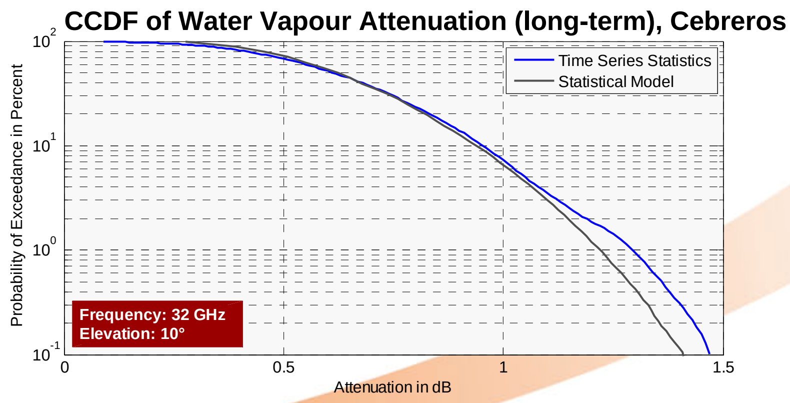
Atmospheric Attenuation Model
Time Series Model (3)









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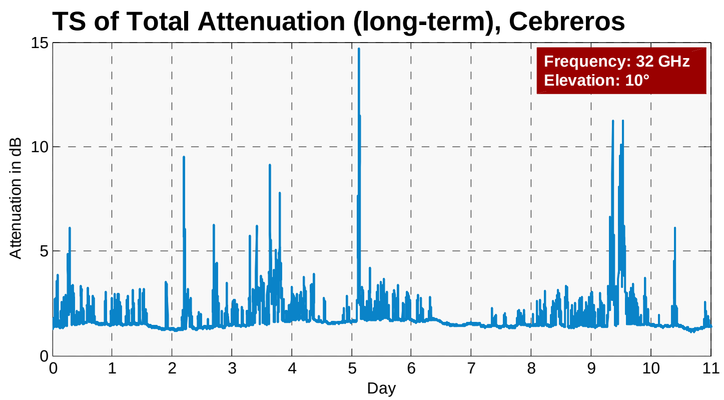
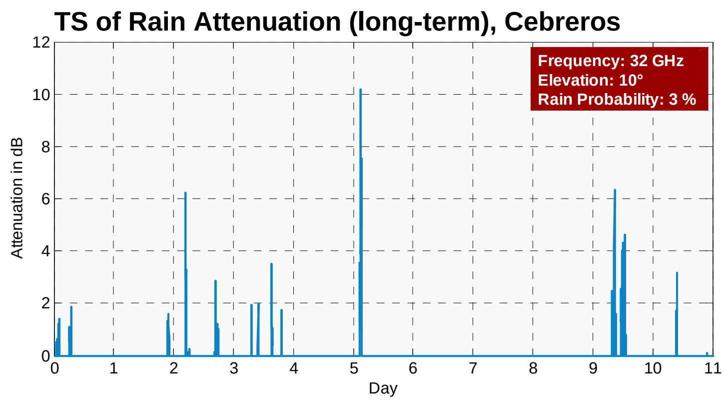
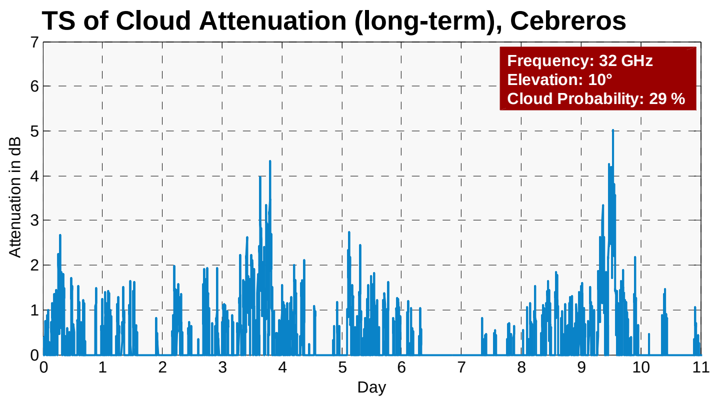
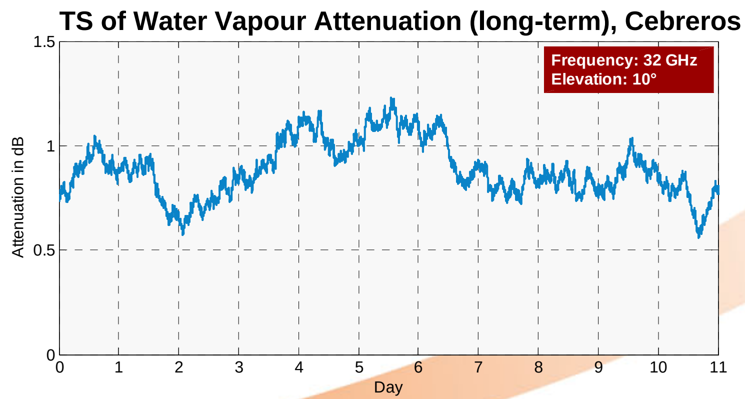
Atmospheric Attenuation Model
Time Series Model (4)









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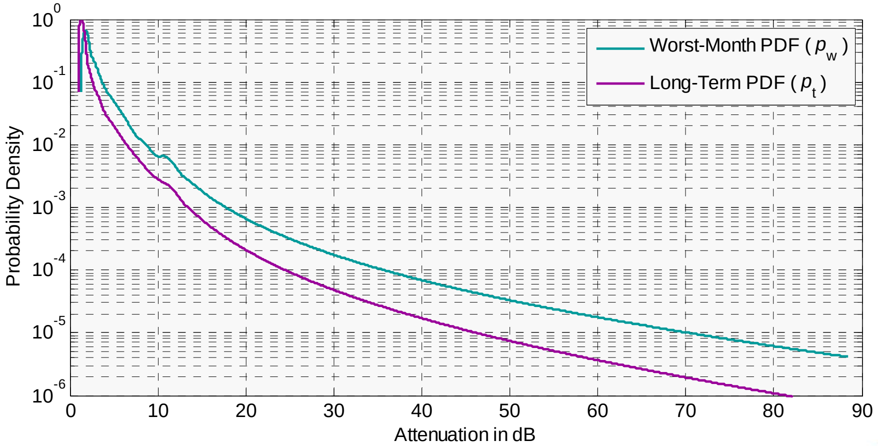
Atmospheric Attenuation Model
Time Series Model (5)

- **Worst-month conversion** is performed by multiplication by a dynamic factor being the quotient of two random variables.
- The numerator of the quotient obeys the distribution of worst-month attenuation, while the denominator obeys the distribution long-term attenuation.
- The respective probability densities (given a certain site, elevation, and frequency) are plotted below:



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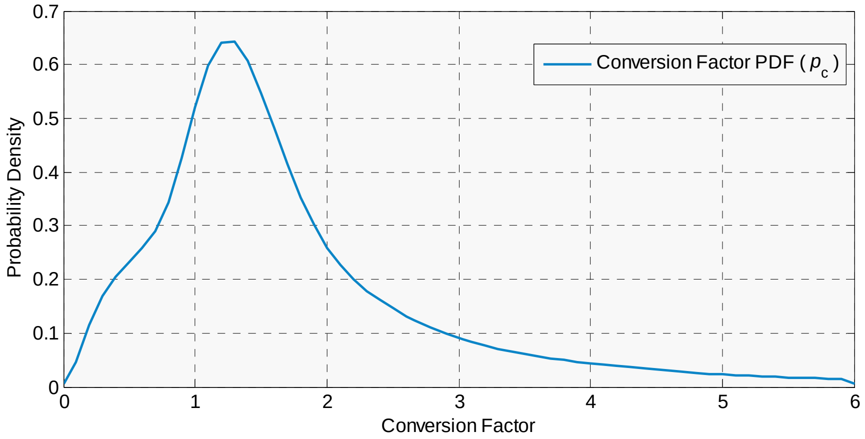
Atmospheric Attenuation Model
Time Series Model (6)

- The probability density of the quotient looks as follows:



- A gliding averaging filter reduces the variation of the random variable such that the values are confined within reasonable boundaries.
- Worst-month conversion is intended to raise the attenuation level but not its rate above average (i.e. by more than the conversion factor itself).
- The speed at which the conversion factor changes is below the rate of the slowest total attenuation contributor.

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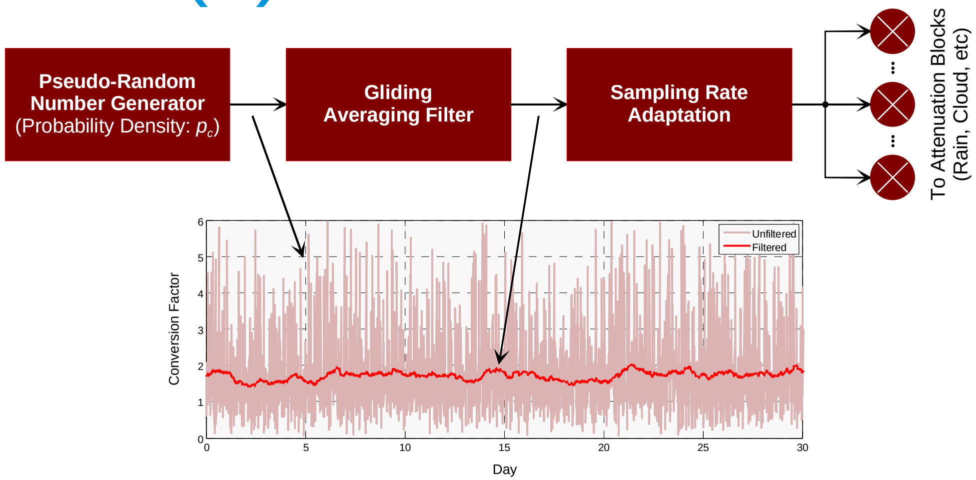
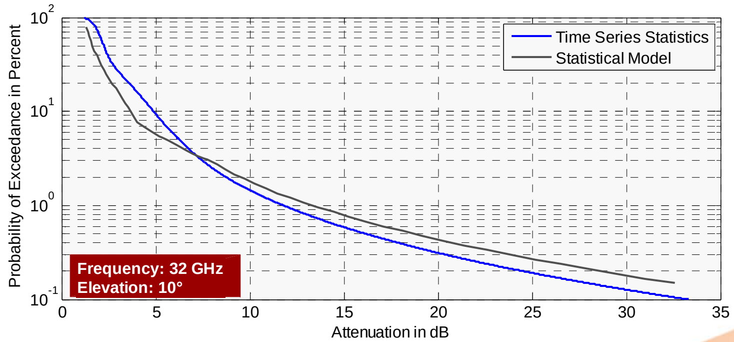
Atmospheric Attenuation Model
Time Series Model (7)

- Block diagram of worst-month conversion algorithm:



- CCDFs of total attenuation:
  $\rightarrow$ curves are fairly similar, albeit don't match as closely as their long-term counterparts



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Link Parameters

- Spacecraft EIRP (including spacecraft antenna pointing loss)
- Channel coding gain
- Residual carrier loss (where applicable)
- Co-polarization loss (negligible)
- Free space path loss
- Atmospheric loss
- Ground station antenna pointing loss
- Ground station G/T
- Implementation loss
- Link margin
- System noise temperature (see next slide)

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System Noise Contributors

- System noise is composed of sky, receiver, and ground noise.
- Sky noise contributors:
  - Cosmic background radiation
  - Galactic noise (neglected)
  - Lunar noise (neglected except for moon rover scenario)
  - Solar noise (may lead to outages in Ganymede and Mercury scenarios)
  - Jovian noise (in Ganymede scenario)
  - Mercurian noise (neglected)
- Receiver noise contributors:
  - Passive resistive equipment in front of LNA and LNA itself
- Ground noise contributors:
  - All surfaces seen by any sidelobe of the ground station antenna

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VCM and DLP Strategies

- Variable coding and modulation (VCM) strategies:
  - Constant data rate during all passes (CCM).
  - Individual data rate for each pass, but constant during a pass (semi VCM).
  - Individual data rate at each 10 second time step (full VCM).
  - All results reported in this presentation are based on full VCM.

- Downlink period (DLP) strategies:
  - Downlink period covers the entire pass (full DLP).
  - Downlink period is located in the centre of each pass (centred DLP).
  - Downlink period is randomly located within each pass (random DLP).
  - Downlink period is located at the beginning of each pass (leading DLP).
  - Downlink period is located at the end of each pass (trailing DLP).
  - All results reported in this presentation are based on centred/random DLP.

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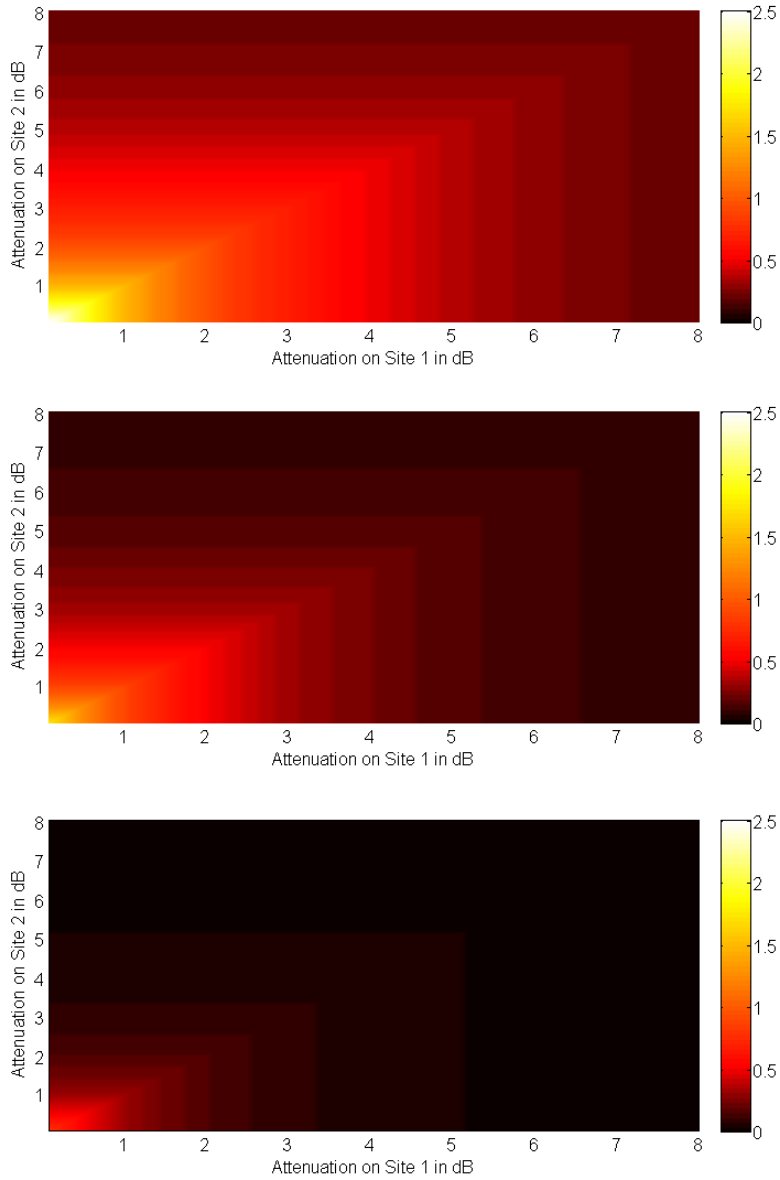
Site Diversity (1)

- Joint probability of rain attenuation exceedance: Probability that the rain attenuation on the downlink path is greater than *y* dB while at the same time the downlink path to a another site in distance
  - 1 km
  - 10 km
  - 50 km

  is greater than *x* dB. For both sites Cebreros rain statistics are assumed.



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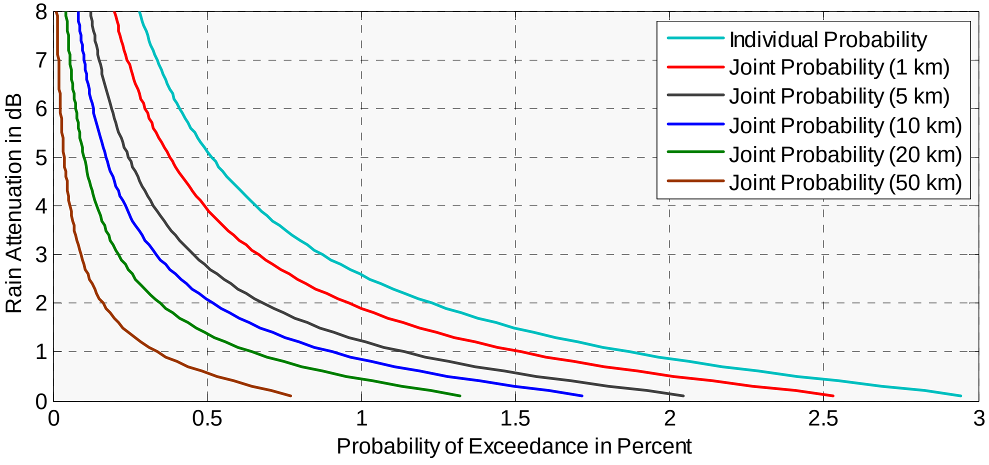
Site Diversity (2)

- Site diversity performance:
  Probability that the rain attenuation on the downlink path to both sites is simultaneously greater than *x* dB in comparison to the probability that the rain attenuation on the downlink path to a single site exceeds the same value.



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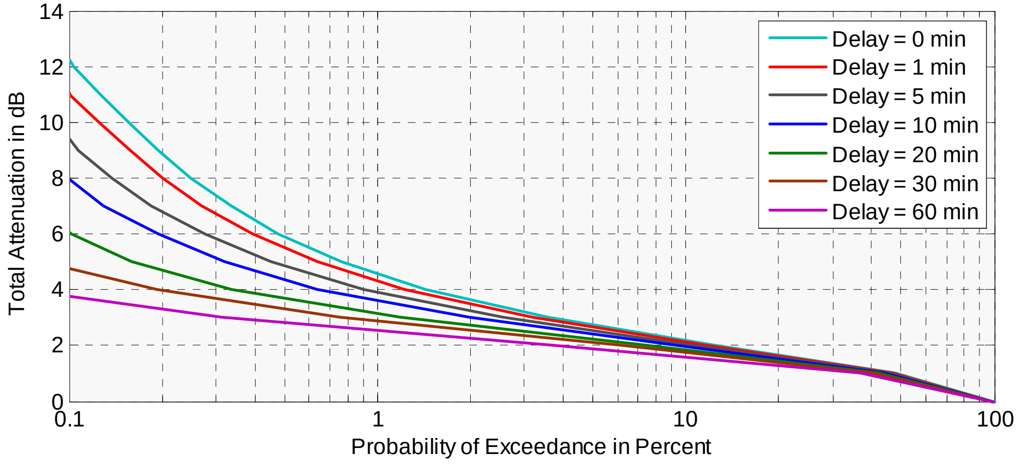
Time Diversity (1)

- Time diversity performance:
  Probability that the attenuation on the downlink path exceeds an attenuation threshold at a given time AND after a certain delay.
- Example below shows time diversity performance on L2-to-Cebreros link assuming worst-month conditions.



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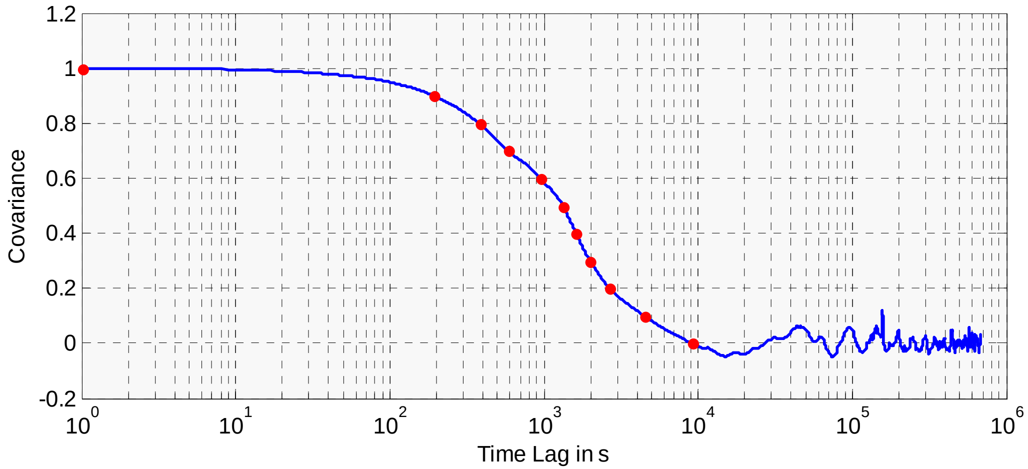
Time Diversity (2)

- Auto-covariance sequence:
  Inverse Fourier transform of power spectrum. Indicator of self-similarity of time series (memory of underlying process).
- Example below shows auto-covariance sequence of attenuation on L2-to-Cebreros link assuming worst-month conditions.



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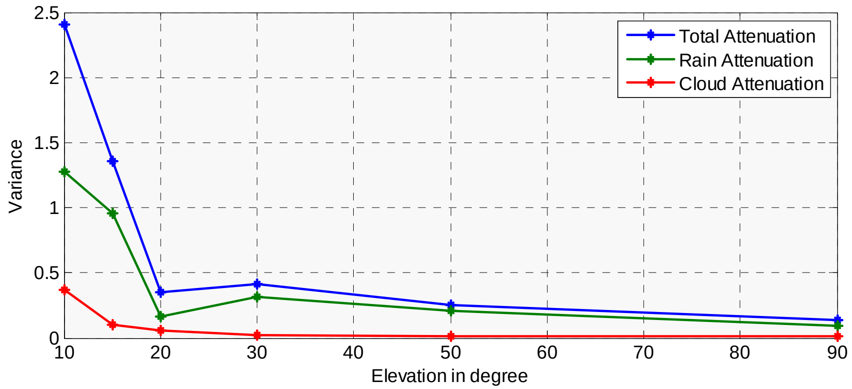
Recommendations for Data Retransmission (1)

- From the time diversity plots on the preceding slides it is apparent that data retransmission should not be performed immediately after data loss detection.
- This is particularly true on links having relatively short round-trip-times (L2 mission: RTT $\approx$ 10 s).
- The optimum is achieved when the joint probability that data gets lost twice (i.e. also during retransmission) is the square of the data loss probability during a single attempt.
- This means that the atmospheric attenuation during retransmission shall only be weakly correlated with the attenuation during the first attempt.
- Avoid immediate retransmissions. Try to exploit time diversity gain. Wherever feasible, wait 30 minutes or more.

Recommendations for Data Retransmission (2)

- Example below shows variance of attenuation vs. elevation on the L2-to-Cebreros link assuming long-term conditions.



- With full VCM the link margin does not depend on the elevation.
- But this applies only to its average. The instantaneous margin tends to rise (i.e. the variance falls) as the elevation goes up.
- Wherever feasible, avoid retransmissions at very low elevations.

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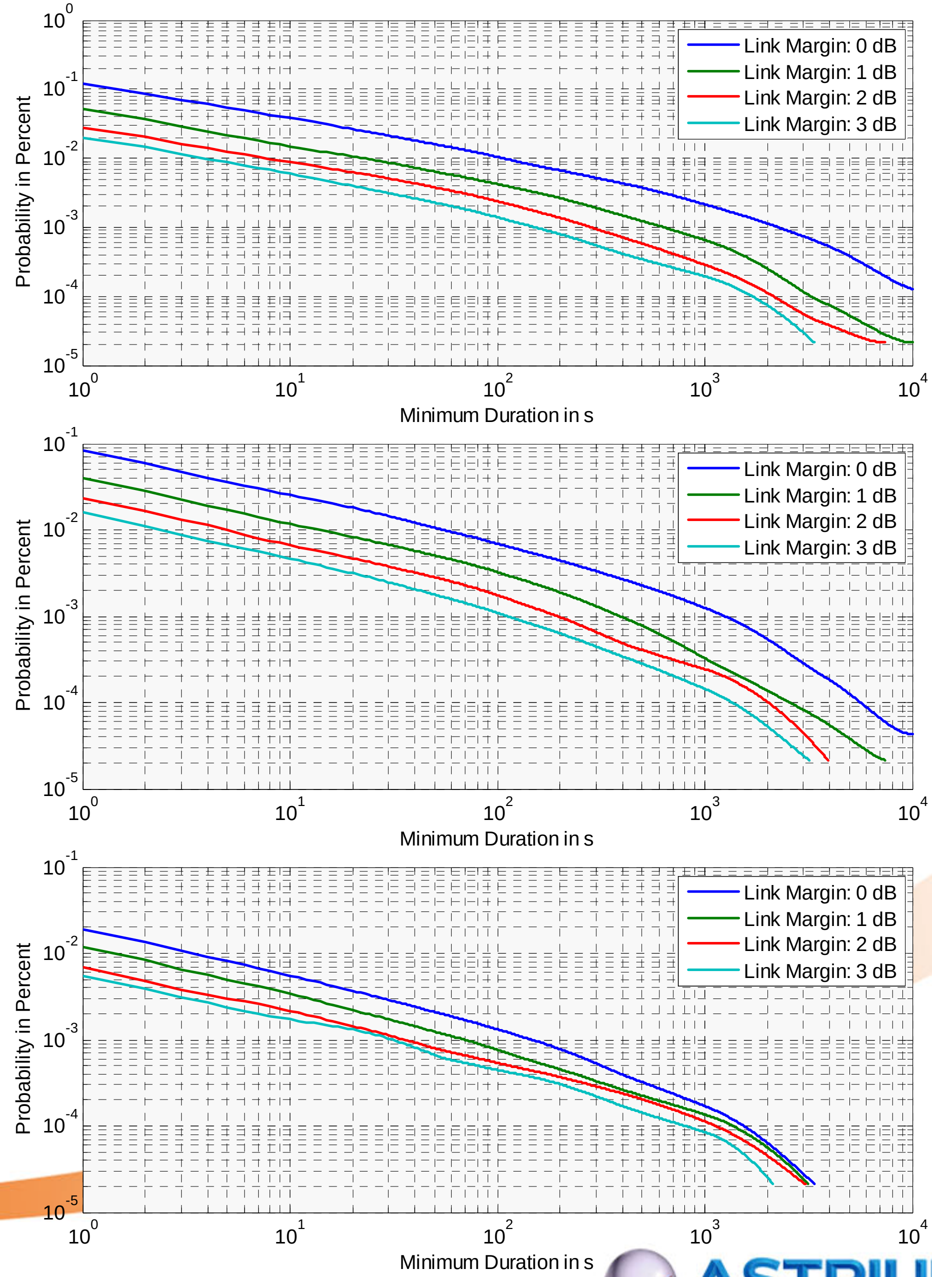
Outage Statistics

- Probability of outage duration is affected by link availability (CD value) and link margin.
- Figures show statistics of L2-to-Cebreros scenario assuming worst-month conditions and CD values
  - 90 %,
  - 94 %,
  - 98 %.
- Probability of outage duration of e.g. ≥ 30 min is between 4×10^{-5} and 1.5×10^{-3} percent in the examples shown here.



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Impact of Timeliness Requirement (1)

- Timeliness requirement for L2 scenario:
  99 percent of data shall be delivered within 24 hours.
- Let T_p and T_d denote the pass and data downlink duration respectively. T_p is variable whereas T_d is constant. $T_d \leq T_p$.
- With **centred** DLP the time between the end of downlink #*n* and the beginning of downlink #*n*+1 is given by $24\text{ h} - T_d$ (neglecting change of declination between contiguous passes).
- With **random** DLP the maximum time between the end of downlink #*n* and the beginning of downlink #*n*+1 is given by $24\text{ h} + T_p - 2T_d$.

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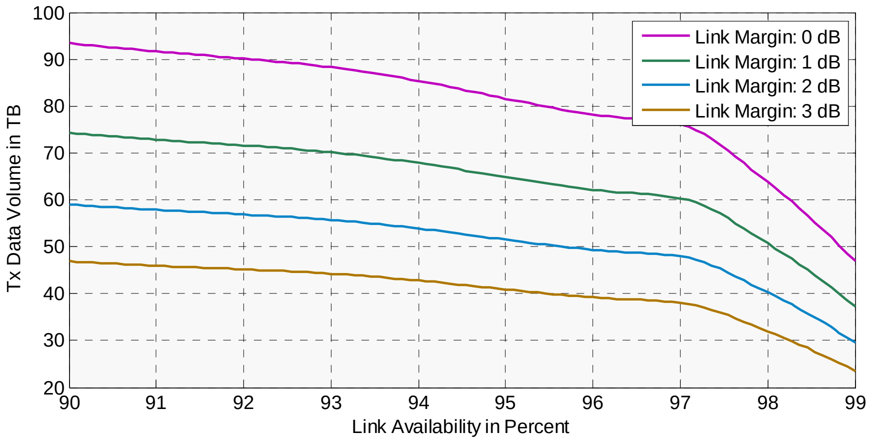
Impact of Timeliness Requirement (2)

- In the L2 scenario T_p varies between 5 h and 14 h. As per specification the downlink duration is given by $T_d = 3.5$ h.
- For **centred** DLP it follows that 24 h – 3.5 h = 20.5 h is the gap between two contiguous downlink periods.
- For **random** DLP it follows that 24 h + 14 h – 7 h = 31 h is the maximum gap between two contiguous downlink periods. This gap exceeds the permissible timeliness range.
- I.e. during phases where the Earth's declination enables long passes, **random** DLP may cause violation of the timeliness requirement if more than 1 percent of data is lost during a downlink period.

Optimum Link Operation Concepts (1)

- Highest yearly data volume for a given on-board EIRP
  - use centred DLP
  - use 0 dB link margin
  - use low link availability (CD value)
  - assume long-term conditions for statistical data



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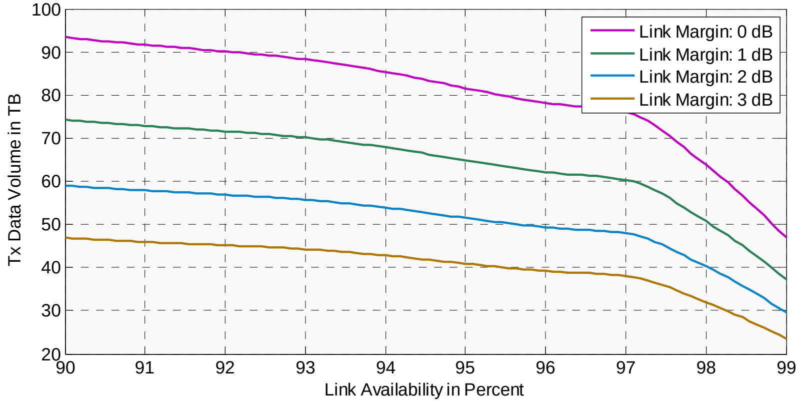
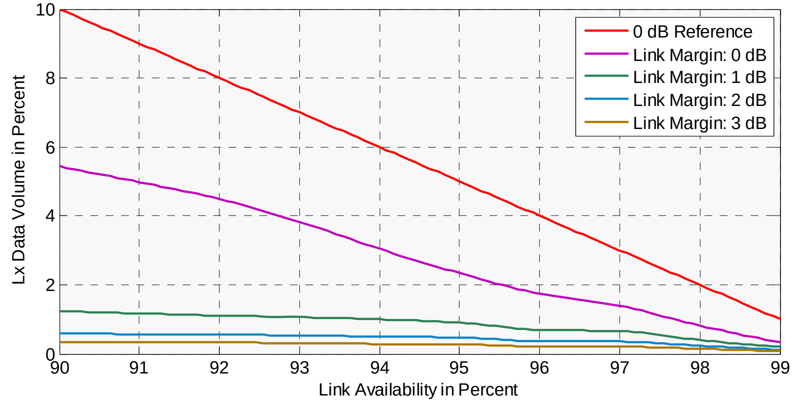
Optimum Link Operation Concepts (2)

- Highest data volume for a given on-board EIRP and a specified maximum yearly percentage of permanent data loss
  - use centred DLP
  - use 0 dB link margin
  - select link availability (CD value) such that ordinate of magenta curve equals specified percentage of permanent data loss
  - assume long-term conditions for statistical data





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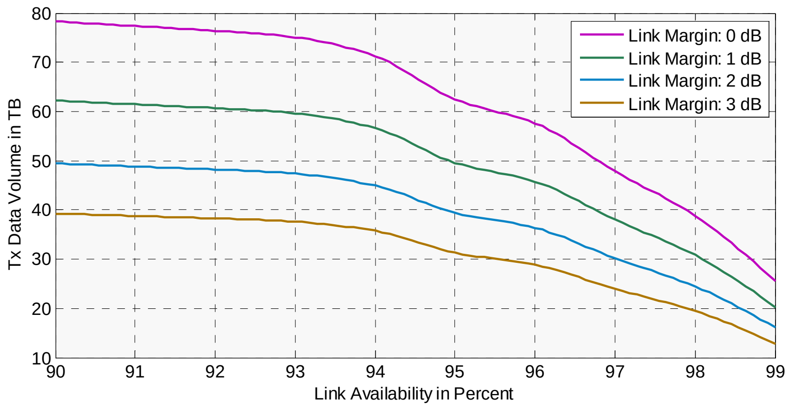
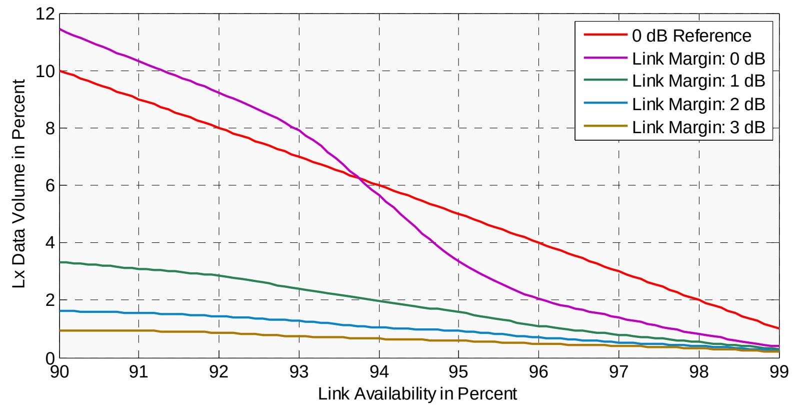
Optimum Link Operation Concepts (3)

- Highest data volume for a given on-board EIRP and a specified maximum monthly percentage of permanent data loss
  - use centred DLP
  - use 0 dB or 1 dB link margin
  - select link availability (CD value) such that ordinate of magenta or green curve equals specified percentage of permanent data loss
  - assume worst-month conditions for statistical data





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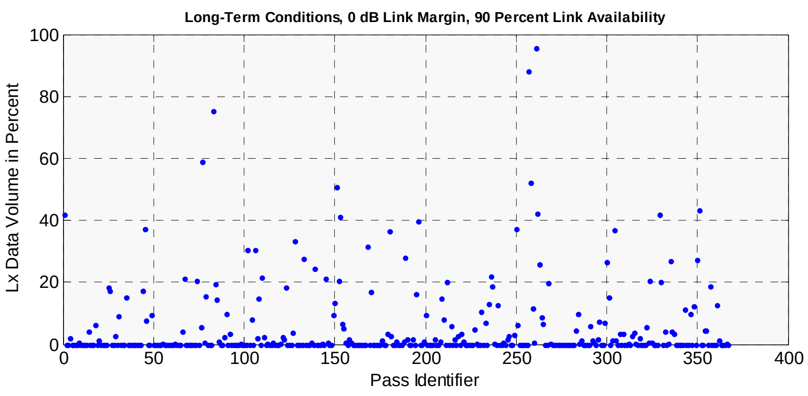
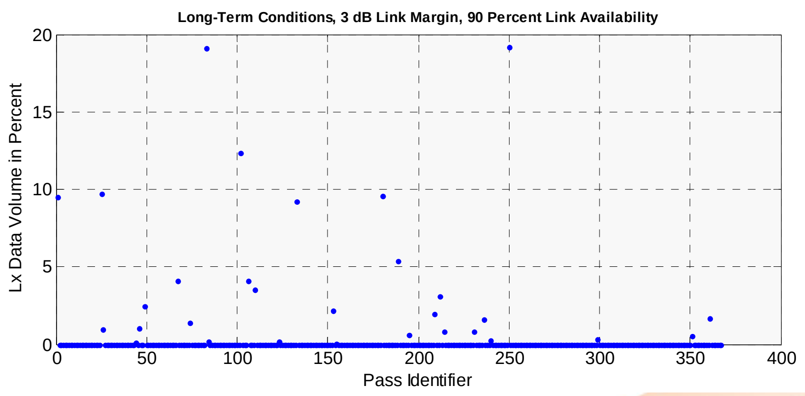
Optimum Link Operation Concepts (4)

- Highest data volume for a given on-board EIRP and a specified maximum yearly average percentage of data not delivered within a specified timeliness range

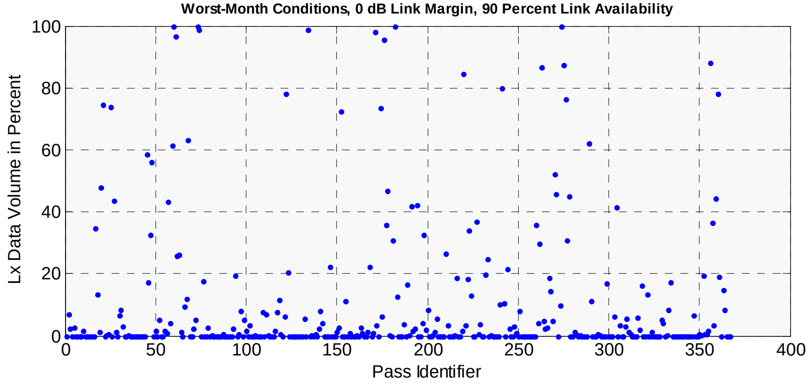


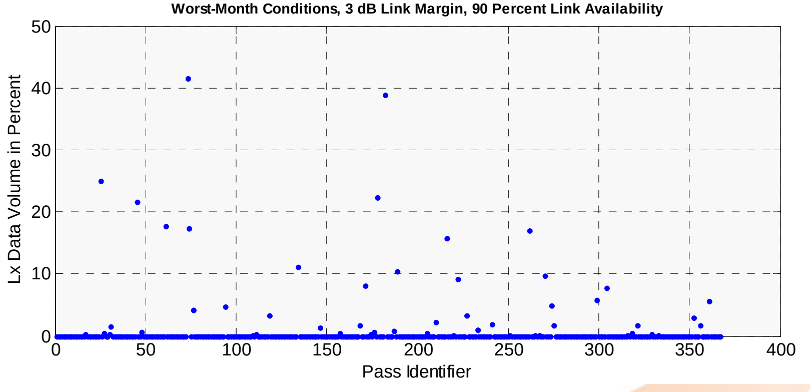


All the space you need

Optimum Link Operation Concepts (5)

- Highest data volume for a given on-board EIRP and a specified maximum monthly average percentage of data not delivered within a specified timeliness range





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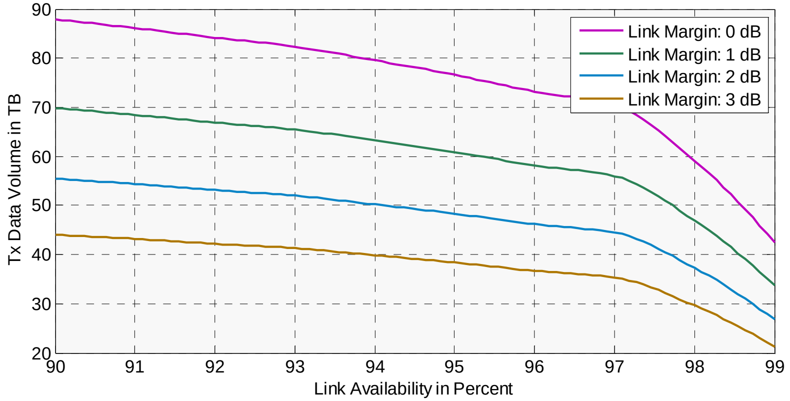
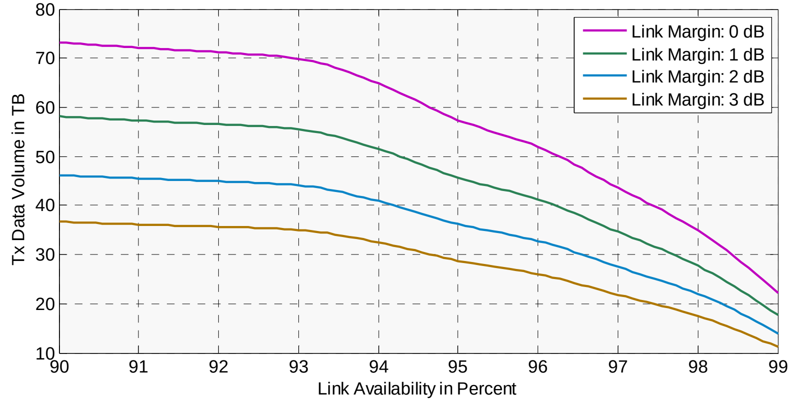
Optimum Link Operation Concepts (6)

- For comparison the data volumes using random instead of centred DLP are shown below.
  - Left hand side: long-term conditions
  - Right hand side: worst-month conditions
- The differences to centred DLP are perceptible, but not dramatic. Random DLP provides roughly 5 to 10 percent less data volume.





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Protocols (1)

- The K/Ka-Band data downlink resembles an erasure channel.
- Data packets are either received correctly or are lost.
- Approaches to handle data loss are:
  - Ignore lost packets (only possible if data is uncritical).
  - Attempt to retrieve lost packets by requesting retransmissions (transport layer protocol, e.g. CFDP).
  - Attempt to retrieve lost packets from the correctly received ones (e.g. long erasure coding).

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Protocols (2)

- **CFDP** is a transport layer protocol that permits the receiver to request retransmission of data packets.
- CFDP supports negative acknowledgements. By means of NAKs the receiver informs the sender about discontinuities in the downlink data stream (data loss), thus triggering retransmission.
- Four NAK options are available: deferred, immediate, prompted, and asynchronous. The "asynchronous" option appears to be the most appropriate for the given application as it maximises the receiver's control and enables optimum exploitation of time diversity gain.
- The signalling channel used for exchanging CFDP protocol messages like positive and negative acknowledgements, end-of-file messages, etc must be bidirectional.

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Protocols (3)

- The reliability of the signalling channel should be significantly higher than the one of the data downlink.
- CFDP is robust and can, to a certain extent, cope with corrupted and lost protocol messages.
- However, in the event of unreliable signalling overhead and delay increase and it may even come to data loss by buffer overflow.
- If available, signalling via S- or X-Band TM/TC could be used for the reliable exchange of CFDP protocol messages.

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Protocols (4)

- **Long erasure codes** avoid some drawbacks of CFDP.
- They have no demand for bidirectional and/or reliable signalling.
- Their redundancy packets are multiplexed into the data downlink stream.
- However, they also have some major disadvantages:
  - They permanently generate redundancy (overhead) even if the link conditions are okay such that no data loss occurs.
  - Unless a feedback path is introduced, they cannot react on adverse atmospheric conditions, even if they are rateless (like raptor codes).
  - In a statistical sense this could be mitigated, e.g. by generating more redundancy at low elevation angles and less redundancy at high elevation angles.
  - In order to cope with the outage durations on the K/Ka-Band link, the codewords have to be impractically long. Interleaving may help to overcome this problem, but the mechanism would be cumbersome.