Ka-Band Propagation Experiment in French Guiana
CNES R&T Study: R-S15/TC-0005-66

April 7th, 2021

ONERA : Xavier Boulanger (until September 2019), Charles-Antoine L’Hour, Jean-Pascal Monvoisin, Laurent Castanet
CNES : Bouchra Benammar, Xavier Boulanger (from September 2019)
CSG : Adrien Lanon, Coline Brunner, Ingrid Epailly
Outline

- Context of the study
- Description of the propagation experiment
- Data processing
- Statistical analysis and results
- Conclusion and perspectives
- Discussion
Context of the study

- **Worldwide and central/latin America Ka-band satellite services**
  - INMARSAT GlobalXpress (worldwide):
    - 5-satellites constellation (since 2019),
    - Broadband telecommunication services
  - EUTELSAT:
    - E65WA (Latin America, since 2016)
    - Coming services for Africa with other satellites

- **Need for characterization of the Earth-space propagation channel**
  - Improvement of prediction models & particularly ITU-R Recommendations
  - System design: link margins & availability assessment: annual, monthly, hourly

- **Need for measured data with high quality and availability**
  - Parameters to be characterized:
    - Rain and total attenuation, scintillation, sky noise temperature, dépolarization
    - Rainfall rate, ILWC, IWVC
  - Reliable data processing: validated attenuation time series to compute statistics
Outline

- Context of the study
- Description of the propagation experiment
- Data processing
- Statistical analysis and results
- Conclusion and perspectives
- Discussion
Description of the propagation experiment

Space segment

<table>
<thead>
<tr>
<th>Satellite name</th>
<th>Amazonas 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit type</td>
<td>GEO</td>
</tr>
<tr>
<td>Orbit position</td>
<td>61°W</td>
</tr>
<tr>
<td>Frequency</td>
<td>20.1995 GHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>RHCP</td>
</tr>
<tr>
<td>EIRP</td>
<td>≈ 20 dBW *</td>
</tr>
</tbody>
</table>

* Estimated from ONERA link budget and Rx dynamic range
Description of the propagation experiment

Installation site: French Guiana Space Centre in Kourou

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Altitude (km)</th>
<th>Elevation (°)</th>
<th>Azimuth (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSG Kourou</td>
<td>5.1713</td>
<td>-52.6862</td>
<td>0.013</td>
<td>78.49</td>
<td>238.36</td>
</tr>
</tbody>
</table>
Description of the propagation experiment

Ground segment

- Ka-Band beacon receiver (2017-2020)
- Tipping bucket rain gauge (2017-2020)
- Tersus GNSS receiver (2018-2020)
Partnerships and schedule

• Partnerships

• Schedule

<table>
<thead>
<tr>
<th>Equipment installation</th>
<th>December, 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning of measurements</td>
<td>January, 2017</td>
</tr>
<tr>
<td>End of measurements</td>
<td>December 2020</td>
</tr>
</tbody>
</table>
Outline

• Context of the study
• Description of the propagation experiment
• Data processing
• Statistical analysis and results
• Conclusion and perspectives
• Discussion
Data processing
Overview

- **Beacon receiver**
  - Raw data (receiver power time series)
    - Beacon processing
    - Processed data (in-excess attenuation time series)

- **Rain gauge**
  - Raw data (tips)
    - Rain gauge processing
    - Processed data (rain rates time series)

- **GNSS receiver**
  - Raw data (GNSS observation & navigation files)
    - GNSS receiver processing
    - Processed data (IWVC)
Data processing

Processing overview

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEVEL 0: Measured Instrumental Data (MID)</td>
<td>Raw data acquired and/or retrieved by the measuring instruments (Beacon Receiver, Radiometer and Rain Gauge) often in several files. Instruments usually provide a time stamp, an alarm flag and data in private format.</td>
<td>Raw data acquired and/or retrieved by the measuring instruments (Beacon Receiver, Radiometer and Rain Gauge) often in several files. Instruments usually provide a time stamp, an alarm flag and data in private format.</td>
</tr>
<tr>
<td>LEVEL 1: Raw Propagation Data (RPD)</td>
<td>Data are referenced to synchronized time stamp and standard format for data and validity flag values (by assignment or conversion of MID data / time stamp / alarm flag). Measurements are grouped in daily files.</td>
<td>Output of the combination of MID files</td>
</tr>
<tr>
<td>LEVEL 2: Intermediate Propagation Data (IPD)</td>
<td>Data processing to retrieve in-excess attenuation and rainfall rate. Measurements are grouped in daily files.</td>
<td>Raw propagation data (RPD)</td>
</tr>
<tr>
<td>LEVEL 3: Validated Time Series (VTS)</td>
<td>Statistical results extracted from VTS.</td>
<td>Validated propagation data (IPD)</td>
</tr>
<tr>
<td>LEVEL 4: Analyzed Experimental Statistics (AES)</td>
<td>Statistical distributions of the propagation parameters are calculated from VTS.</td>
<td>Analyzed experimental statistics (AES)</td>
</tr>
</tbody>
</table>

LEVEL 0: Measured Instrumental Data (MID)
- Acquired and/or retrieved by the instruments (Beacon Receiver, Radiometer and Rain Gauge)
- Standard time stamp is provided
- Instrumental alarm flags are usually provided

From MID to RPD (Combination of MID files)
- Set data to synchronized time stamp
- Set standard validity flags
- Converting parameters to standard format and unit

LEVEL 1: Raw Propagation Data (RPD)
- Synchronized time stamp is provided
- Standard validity flags are provided

From RPD to IPD (1st data processing)
- Automatic spikes detection on beacon data
- Final assessment of validity flags of beacon data by visual inspection
- If available: Retrieval of integrated water contents (if modification w.r.t. MID output) and final assessment of validity flags of radiometer data by visual inspection
- If available: Computation of rainfall rate and final assessment of validity flags of rain gauge data by visual inspection
- Daily template extraction (FFT or other method)

LEVEL 2: Intermediate Propagation Data (IPD)
- Calibrated beacon data (without daily template)
- Equivalent to in-excess attenuation and rainfall rate data
- Synchronized time stamp is provided
- New validity flags are provided

From IPD to VTS (2nd data processing)
- Data processing to retrieve in-excess attenuation
- Rain events detection methodology
- Saving time series of required parameters
- Saving final validity flags

LEVEL 3: Validated Time Series (VTS)
- Time series of required parameters in Global archive format
- Synchronized time stamp is provided
- Final validity flags are provided

From VTS to AES (3rd data processing)
- Computation of statistics

LEVEL 4: Analyzed Experimental Statistics (AES)
- Statistical results extracted from VTS
Data processing
Beacon processing

Raw Propagation Data (L0-L1)

1. Automatic pre-processing procedures (outliers removal, rough reference level)
2. Identification of rain events based on concurrent rainfall rate data (high correlation due to high elevation angle: \(\approx 80^\circ\))
3. The beginning and the end of each rain attenuation event are manually adjusted
Data processing

**GNSS receiver processing**

 rinex → **CSRS** → $z_{td}$  

 location → **SYNOP** → $z_{hd}$  

\[
\Pi = \frac{10^6 M_w}{\rho R \left( k_2 - k_1 \frac{M_w}{M_d} + \frac{k_3}{T_m} \right)} \]

$IWVC = \Pi \cdot zw_{d}$

$IWVC$ → **ITU-R P.676-12 (Annex 2)** → **Water vapour attenuation**


SYNOP  Surface meteorological data provided by Météo France public service (https://donneespubliques.meteofrance.fr/?fond=produit&id_produit=91&id_rubrique=32)
GNSS receiver based IWVC
IWVC time series and statistics

Integrated Water Vapour Content
2018

Integrated Water Vapour Content
2020

CCDF of Integrated Water Vapour Content
2018

CCDF of Integrated Water Vapour Content
2020

Ka-Band Propagation Experiment in French Guiana
Outline

• Context of the study
• Description of the propagation experiment
• Data processing
• Statistical analysis and results
• Conclusion and perspectives
• Discussion
Statistical analysis and results
Data availability

<table>
<thead>
<tr>
<th>Equipment</th>
<th>2017</th>
<th>2018</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beacon receiver</td>
<td>99.65</td>
<td>99.73</td>
<td>99.41</td>
</tr>
<tr>
<td>Rain gauge</td>
<td>99.75</td>
<td>100</td>
<td>99.50</td>
</tr>
<tr>
<td>GNSS receiver</td>
<td>80.01</td>
<td>96.22</td>
<td></td>
</tr>
</tbody>
</table>

Annual valid propagation data (%) by equipment
Statistical analysis and results
Annual statistics of rainfall rate and rain attenuation

Inter-annual variability:

<table>
<thead>
<tr>
<th></th>
<th>2017</th>
<th>2018</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 %</td>
<td>8 mm/h</td>
<td>6 mm/h</td>
<td>5 mm/h</td>
</tr>
<tr>
<td>0.5 %</td>
<td>20 mm/h</td>
<td>14 mm/h</td>
<td>15 mm/h</td>
</tr>
<tr>
<td>0.1 %</td>
<td>50 mm/h</td>
<td>38 mm/h</td>
<td>40 mm/h</td>
</tr>
</tbody>
</table>

P.837-7: annual $M_f$ maps close to experimental values, but log-normal distribution not suitable in tropical-equatorial region

Inter-annual variability:

<table>
<thead>
<tr>
<th></th>
<th>2017</th>
<th>2018</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 %</td>
<td>4 dB</td>
<td>2.3 dB</td>
<td>2.6 dB</td>
</tr>
<tr>
<td>0.5 %</td>
<td>7.5 dB</td>
<td>5 dB</td>
<td>6 dB</td>
</tr>
<tr>
<td>0.1 %</td>
<td>22 dB</td>
<td>14 dB</td>
<td>19 dB</td>
</tr>
</tbody>
</table>

Better prediction using $R_{0.01}$ vs modelled $R_{0.01}$
Biais for $p > 1$
In-excess attenuation: total attenuation would need clear-sky attenuation
Statistical analysis and results
Monthly statistics of rainfall rate

High seasonal variability due to seasonal climate characteristics

More years of data → more reliable mean CCDF

Need to keep collecting data in long term in order to compute reliable statistics vs seasonal variability
Statistical analysis and results

Very High seasonal variability due to seasonal climate characteristics

More years of data → more reliable mean CCDF

Need to keep collecting data in long term in order to compute reliable statistics vs seasonal variability
Statistical analysis and results
Seasonal analysis

Dry:
- August
- September
- October

Inter:
- January
- February
- March
- July
- November
- December

Wet:
- April
- May
- June

<table>
<thead>
<tr>
<th>Probability of exceedance (%)</th>
<th>dry</th>
<th>inter.</th>
<th>wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 %</td>
<td>0.3 dB</td>
<td>3 dB</td>
<td>7 dB</td>
</tr>
<tr>
<td>0.5 %</td>
<td>1 dB</td>
<td>5.5 dB</td>
<td>11 dB</td>
</tr>
<tr>
<td>0.1 %</td>
<td>7 dB</td>
<td>15.5 dB</td>
<td>&gt;22 dB</td>
</tr>
</tbody>
</table>
Statistical analysis and results
Hourly statistics of rate attenuation

Rain attenuation concentrated around from 0h to 12h local time

Inter-annual variability
Outline

• Context of the study
• Description of the propagation experiment
• Data processing
• Statistical analysis and results
• Conclusion and perspectives
• Discussion
Conclusion and perspectives

3 years of processed rainfall rates and rain attenuation data in equatorial area with excellent availability (one of the best in the World in 2017-18-20)

Variability of the propagation channel

- Annual, seasonal, monthly and hourly analyses available
  - 2017 very rainy, especially in January and December
  - 2020 very dry from January to March
- 8 dB difference between the most favourable year and the worst year at 0.1 %
- 20 dB difference between the most favourable month and the worst month at 0.2 %

Comparisons with prediction methods in Recommendations ITU-R P.837-7 (rainfall rate) and ITU-R P.618-13 (rain attenuation)

- Significant differences wrt. ITU-R P.837-7 for probability of exceedance $< 10^{-2}$ %
- Good results wrt. ITU-R P.618-13 for % below 1% but poor results above

2 years of IWVC data in equatorial area with excellent availability
Conclusion and perspectives

Strong inter-annual and inter-month variabilities (in a 3 years long experiment only) that strongly suggest to extend the collection data to derive reliable CCDFs.

Need support to extend propagation experiment

Improvement of the dynamic range of the measurements in order to improve the statistical analyses (e.g. by the use the E65WA Ka-band beacon and by replacing the beacon receiver by an SDR-based ones)

Add ancillary equipments to the ground segment to collect other meteorological data (radiometer, micro-rain radar, disdrometer, etc.)

Set up a diversity experiment in tropical area using other sites in French Guiana (two sites under investigation: Cayenne airport and Montagne des Pères)

Kourou vs other sites in French Guiana
Outline

• Context of the study
• Description of the propagation experiment
• Data processing
• Statistical analysis and results
• Conclusion and perspectives
• Discussion
Appendices
Statistical analysis and results
Rain amount

Rain Amount

<table>
<thead>
<tr>
<th>Month</th>
<th>2017</th>
<th>2018</th>
<th>2020</th>
<th>ITU-R P.837-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Data processing
Rain gauge processing

Tips
IAP recommended method (Sliding window derivative of accumulated rain amount)

RR

IAP Institute of Atmospheric Physics
Statistical analysis and results
Inter-annual variability of monthly statistics of rain attenuation

CCDF of rain attenuation
- March
  - March 2017
  - March 2018
  - March 2020
  - March (total)

- April
  - April 2017
  - April 2018
  - April 2020
  - April (total)

- May
  - May 2017
  - May 2018
  - May 2020
  - May (total)

CCDF of rain attenuation
- September
  - September 2017
  - September 2018
  - September 2020
  - September (total)