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TP Meteoserver

Final LVNL Evaluation report

To conclude the development phase

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Author(s)	
Name	**Function**
Paul de Kraker	TP-MeteoServer Project Leader

Review			
Name	**Function**	**Version**	**Date**
Ferdinand Dijkstra	ATMS expert LVNL	0.8	07-jan-2010
Siebren de Haan	Meteo expert	0.8	12-jan-2010
Louis Bailey	Boeing project lead	0.8	07-jan-2010

Approval (by document owner)			
Name	**Function**	**Signature**	**Date**
Evert Westerveld	MT KDC	[signature]	15.01.2010

Acceptance (by client)			
Name	**Function**	**Signature**	**Date**
Hans Offerman	VZ Stratcor	[signature]	18-01-2010

Summary

This report summarizes the results of a number of TP performance evaluations, using subsequent versions of TP-Meteo Server prototypes. Previous reports [ref 1-5] have described part of this work in more detail. This report contains previously unpublished results of some additional tests, based on improvements in the quality analysis and assimilation processes by KNMI.
The results of Boeing part of the TP-MS project, i.e. to uplink meteo data are summarized, only limited results from the trials were available.
The document concludes with a proposal for implementation at KNMI and LVNL.

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1 Introduction

Heading

The Trajectory Prediction (TP) functionality calculates the four-dimensional flight path of an individual flight. The accuracy of these calculations is strongly influenced by the quality of meteorological data. The TP Meteoserver project aims to develop an optimal meteorological service for air traffic control by integrating meteorological data from aircraft with data available at KNMI. With this information 4D flight paths can be calculated with accuracy in the order of seconds. In addition to this the airborne trajectory prediction may be improved by uplinking meteo data derived from this service.
This could lead to benefits in the area of flight-efficiency and to alignment of air- and ground-based trajectory prediction results, which in turn would support a common view by pilot and controller. This would be an enabler for the SARA concept and ultimately for CDA's in a high density TMA.

The challenge

The objective of the TP Meteoserver project is to develop and implement a meteorological service which helps the TP functionality to be more accurate in the calculation of 4D flight paths. For this service meteorological data (wind and temperature) from the Mode-S Enhanced Surveillance data from aircraft will be integrated with KNMI data.

The approach

First meteorological data from aircraft systems have been analysed to determine their possible contribution to the quality of the KNMI data. A first generation of the system has been developed using simulations and prototypes. A real-time prototype has been implemented and was used during the SARA operational trials in April 2009.
The quality of different prototypes has been evaluated by using the data for Trajectory Prediction. The accuracy of this new TP calculation can be compared to the "old" TP calculations. A set of 400 actual trajectories served as the reference test set on which TP performance comparison is done.
Boeing has developed a prototype meteo uplink service (METS), which has been used during the SARA operational trials.

Document scope and purpose

This report summarizes the results of a number of TP performance evaluations, using subsequent versions of TP-Meteo Server prototypes. Previous reports [ref 1-5] have described part of this work in more detail. This report contains previously unpublished results of some additional tests, based on improvements in the quality analysis and assimilation processes by KNMI. The results of Boeing part of the TP-MS project, i.e. to uplink meteo data will be summarized, only limited results from the trials were available.
The document concludes with a proposal for implementation at KNMI and LVNL.

2 Evaluation goals, setup and results

2.1 Evaluation Goals

The LVNL need behind the development of the TP Meteo server is better TP performance, required to enable CDA's in high traffic density area's. The idea that has triggered the TP-Meteo Server development is the possible use of Mode-S derived meteo data, which was promising a high resolution and better accuracy of weather forecasts, i.e. wind and temperature in a 4D grid covering the LVNL area of interest.
The approach of the TP-Meteo Server project has been to find, through incremental prototype development, a feasible design of a system to produce a 4D meteo grid with sufficient accuracy. Sufficient accuracy was defined as: sufficient to support SARA type of operations.[ref-6]. SARA requires a TP accuracy in the order of 10-20 seconds, to support controllers to adhere to Inbound Planning EATs within 30 seconds.

2.2 Evaluation setup

The evalution setup has been described in detail in ref 4 and 5. The main characteristics will be summarized here, illustrated with figures describing the subsequent prototypes.

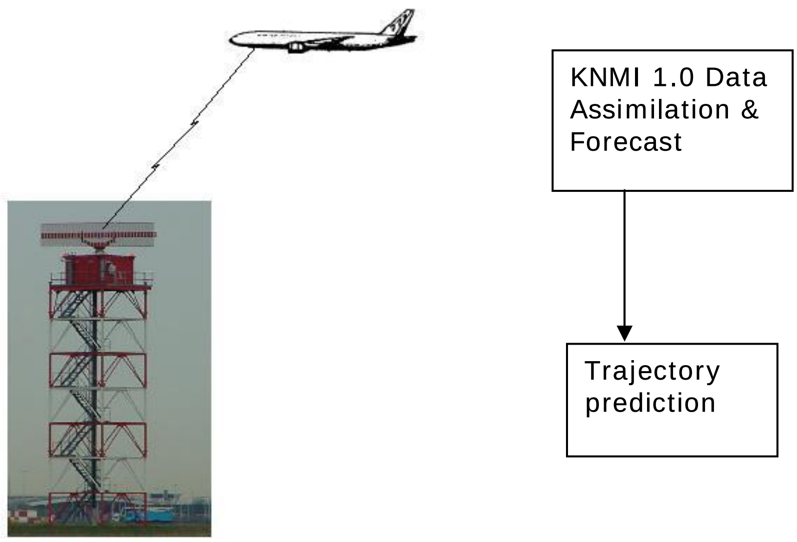

Fig 1. Current Operational Situation.

KNMI1.0 data is a coarse abstract of 4D weather model data (D11) available at KNMI, updated every hour.

Measurement of TP performance is not an easy job. It must be done with the trajectories of actual flights. Apart from meteo conditions other factors have an impact on the predictability of trajectories. The main factors are: aircraft performance characteristics, company policy, pilot and controller interventions causing deviations from the planned route, or standard speed and/or vertical profile. Such deviations cannot be predicted and will therefore cause large

differences between predicted and actual trajectories. Our approach has been to select a set of predictable trajectories from all recorded actual trajectories during a period of about a month. This resulted in a reference trajectory testset of 400 flights, collected during the period of February-March 2008. For these trajectories (in)accurate knowledge of wind and temperature constitutes the main influence on TP performance. This was confirmed by an experiment in which we first assumed the wind vector to be zero and next used a reasonable estimate of wind, derived from KNMI 1.0.
See table 1, chapter 2.3.
In all prototypes we used the TP simulation environment, which contains a TP function with a number of improvements to the current AAA TP. One of the improvements is the ability to interface with TP-Meteo Server. The simulation environment also contains a number of tools for TP performance analysis. These were used to find the results provided in chapter 2.3.

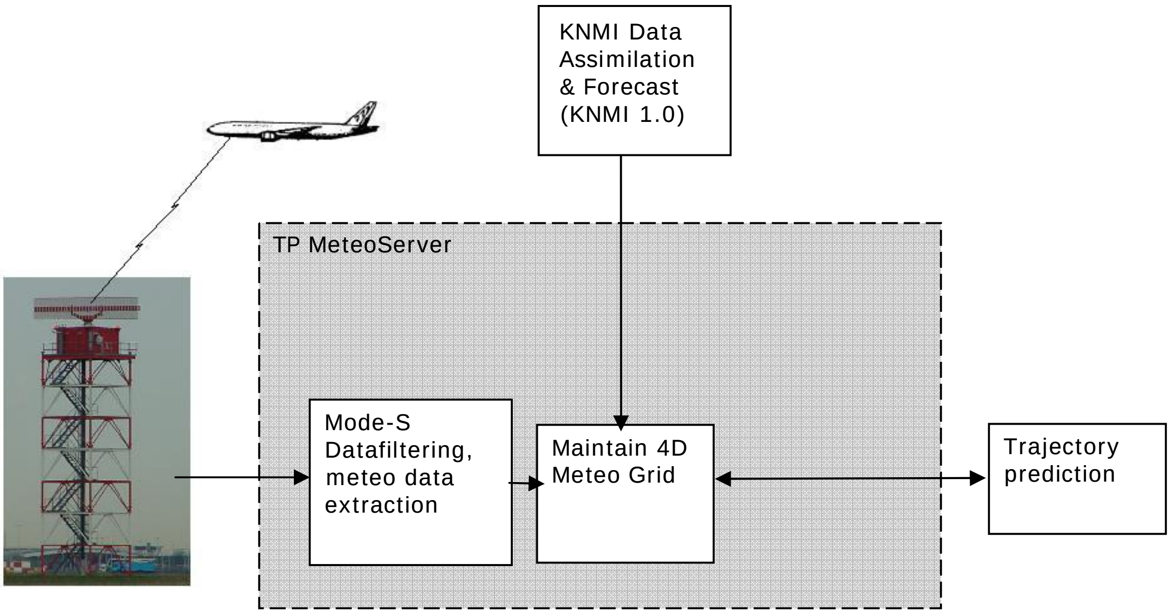

Fig 2. Prototype 0. Mode-S data providing a direct estimate of meteo data.

The first TP-Meteo Server prototype (prototype 0) was using Mode-S derived meteo data only. Wind and temperature for the coming 30 minutes were estimated from a set of measurements derived from EHS data of aircraft present (during the last 10-20minutes) in a box around the predicted positions of the trajectory being calculated. If no sufficient data were available, the KNMI 1.0 data were used.

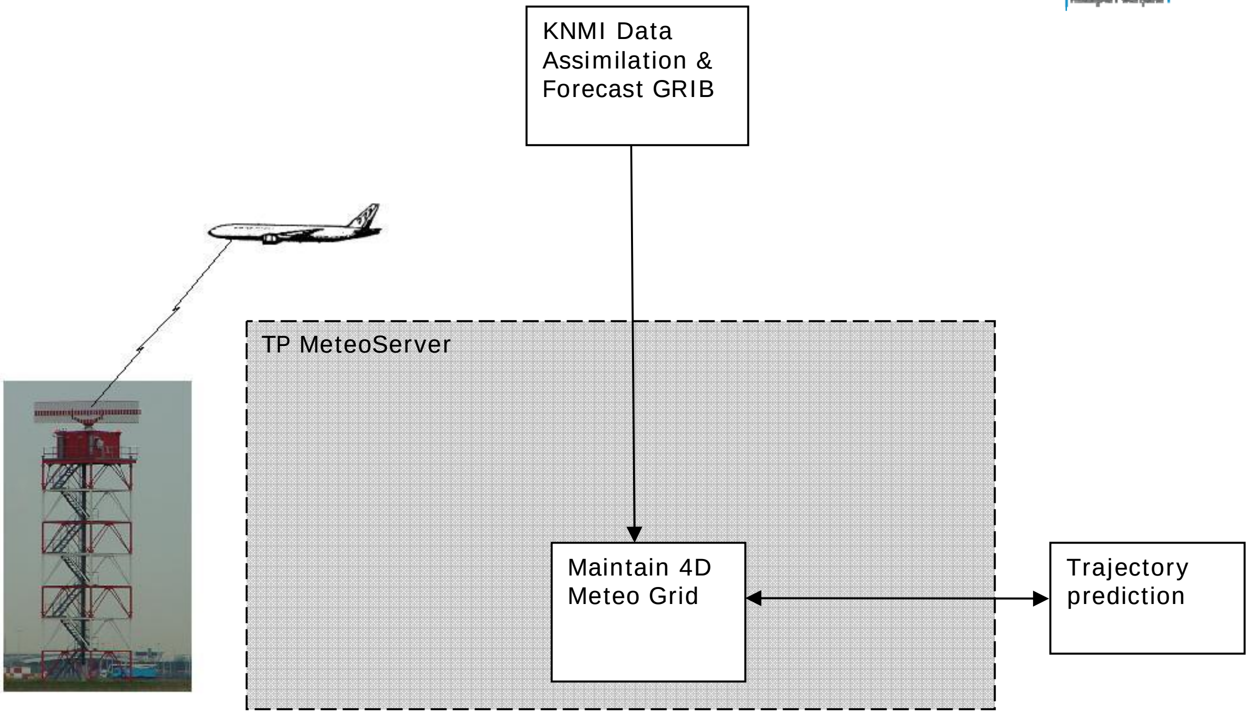

Fig 3. Prototype 1. Use KNMI best available data, no use of Mode-S derived data

The next prototype (prototype 1) was built to measure TP performance with the best available KNMI meteo data, without use of Mode-S data.

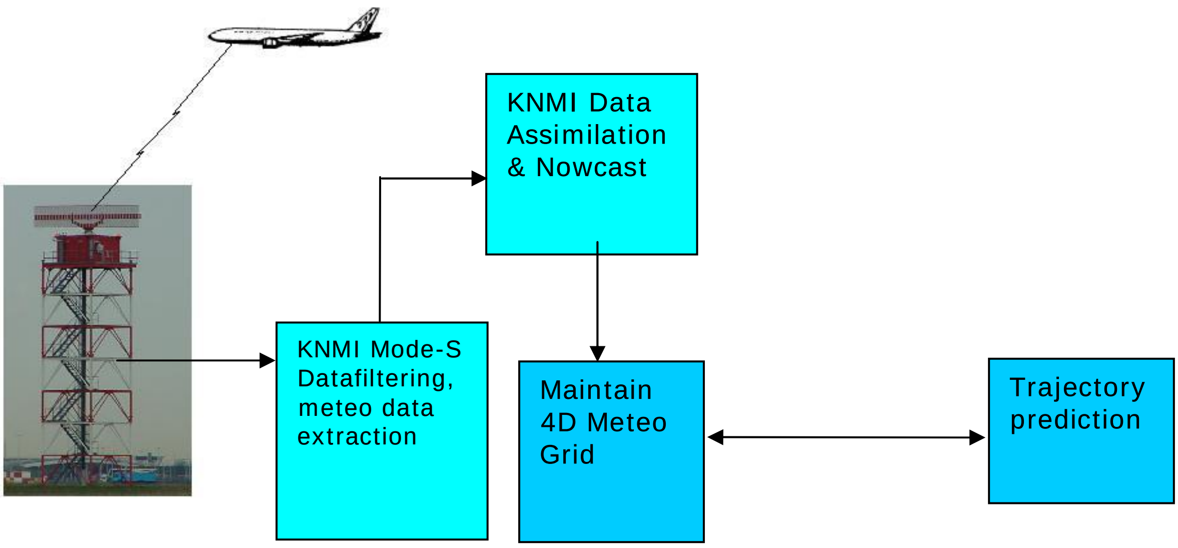

Fig 4. Prototype 2. Mode-S EHS data of TAR-I are sent to KNMI, filtered and assimilated in KNMI weather models

Prototype 2 was built to evaluate TP performance with KNMI meteo data in which Mode-S data were assimilated. KNMI has extensively analysed the quality of EHS

derived meteo data, through comparison with other meteo sources and weather models. This resulted in some significant improvements in the EHS derived data quality. The results of this research are described in a KNMI report [ref 7]. In addition to that KNMI has developed (and is still optimizing) a method to assimilate the Mode-S derived data into their models. This has been done through several improvement steps.
After each step the weather forecasts for the period February, March 2008 were recomputed and were used as input to the TP performance measurement, based on the reference trajectory set. The results of these measurements are summarized in chapter 2.3.

During the SARA operational trials a real-time prototype was used that was built in support of the trials. Because during the implementation of this prototype no results of prototype 2 evaluations were available yet, it was decided to implement the prototype 0 concept and use as a backup the prototype 1 concept. After the trials the SARA flights have been used for evaluation of the prototype 2 performance. This did however not provide us with results that could be compared with other concepts, because the majority of the SARA trajectories contained deviations from the flightplan. The expertise to select predictable flights from the SARA trajectory set was not available and the number of such trajectories was expected to be too small to create a new reference test set. Therefore it was decided to stick to the original reference test set of Feb/March 2008.

The Boeing Meteo uplink function (METS) was used from April 10th till April 27th, including the SARA operational trials, to uplink weather updates, derived from the available KNMI data sources (i.e. D11 and H11 without assimilation of Mode-S). METS used flight information provided by the SARA operational trial platform (NOVA) via datalink between LVNL and Boeing (Seattle) to determine which flight should receive the uplink at which moment. In principle updates were only sent prior to Top Of Descent. The uplink was done through ACARS. 1059 uplinks were made to all KLM aircraft types, except Fokker.

2.3 Evaluation Results

2.3.1 TP-Meteo Server prototype

The results of the above described prototype evaluations are summarized in table 1.
Each row in table 1 provides the statistics of the TP error distribution resulting from the TP testenvironment, using the reference trajectory set and different TP-Meteo server inputs.
Case 1 provides the results when TP was fed with all windvectors set to zero. Compared to the other cases it shows large errors, which can therefore be attributed (for a significant part) to the absence of correct wind information.
Case 2 provides the results when TP was fed with the meteo data currently used in AAA. Already with this rather coarse information the TP performance is significantly improved compared with case 1.
Case 3 provides the results when using the prototype 0 setup. The performance of this relatively simple solution (KNMI 1.0 data is rarely used, most meteo estimates are directly derived from EHS observations, no weather models are used) is remarkable and clearly better than case 2.

Parameter / Case	ETA-ATA@IAF Minimum (s)	ETA-ATA@IAF Maximum (s)	ETA-ATA@IAF Mean (s)	ETA-ATA@IAF St.Dev. (s)
1) No Wind	-293	169	2,3	79,9
2) KNMI 1.0	-83	70	-5,2	20,6
3) PT0 EHS	-64	49	-5,1	17,1
4) PT1 GRIB-4	-64	56	-3,2	17,7
5) PT2 GRIB-M11 March 2009	-61	50	-4,9	17,4
6) PT2 GRIB-M11 September 2009	-60	36	-5,9	16,6
7) PT2.1 GRIB-M11 Use of air-density in TP Nov 2009	-61	38	-4,6	16,7
8) PT2.1 GRIB-M11+AMDAR Nov 2009	-60	36	-4,1	16,8

Table 1: TP performance measurement results with different TP-MS prototype versions

Case 4 provides the results for the prototype 1 setup, when using the best KNMI weather model data available at that time. These data were derived from the

HIRLAM D11 weather model. It is clear that the results for case 4 and case 3 are comparable, although the meteo sources used were different.

Case 5 provides the first results from the prototype 2 setup. The performance improvement was smaller as expected, which strengthened the need to perform a thorough quality analysis of the EHS derived data by KNMI.

This quality analysis showed the possibility to improve the quality of the EHS derived data, through amongst others smoothing, bias correction and improved filtering techniques.

Case 6 provides the results from prototype 2 setup when the improved data extraction was used. We consider the improvement as significant and sufficient evidence to choose for the prototype 2 concept for further implementation.

Case 7 provides the results of a recent test run. The difference with the previous run is the use of airdensity data from M11 in the TP. Airdensity is used in the calculation of TAS from IAS. The formulas used before were based on approximations taking FL and Temperature into account. The bias has significantly decreased, the st.dev. increases slightly, although not significantly.

Case 8 provides the results of the most recent test run, based on an assimilation taking additional AMDAR data from a large area into account. There is no significant effect on the st. dev., but the bias is further reduced. This indicates that extension of the area from which data are used have a positive effect on the TP-MS performance. Extension of the Mode-S coverage area is therefore desirable.

2.3.2 Boeing METS

The results of the METS uplink evaluation as provided by Boeing are summarized in table 2. Although the sample sizes are very different the figures could be indicative of a significant improvement in the difference between planned and actual time at the IAF (delta EAT) due to the combination of SARA and Mets. Flight Operations Quality Assurance (FOQA), which is data recorded from the actual flight for post flight analysis, was unavailable during the SARA trials, therefore it is uncertain if the uplinked weather reports were actually used.

Statistical Parameter of Delta EAT	**Number of Flights**	**Parameter value**
St. Dev with Mets & SARA	36	20.33928 seconds
Mean with Mets & SARA		4.378378 seconds
Min		-30 seconds
Max		50 seconds
St.Dev without Mets & with SARA	234	40.58067 seconds
Mean without Mets & with SARA		4.195745 seconds
Min		-222 seconds
Max		265 seconds
St.Dev without Mets & no SARA	4136	77.23818 seconds
Mean without Mets & no SARA		28.21175 seconds
Min		-272 seconds
Max		639 seconds

Table 2. Delta EAT statistics might indicate a significant improvement due to the combination of SARA and Mets.

3 Business case for implementation

The following questions should be answered now: Are the results as presented in chapter 2 providing sufficient evidence to decide for implementation of one of the concepts? Is the performance improvement achieved by one of the prototyped concepts sufficient to justify the effort of operational implementation? If so, which concept should be implemented?

From chapter 2 it is clear that the current KNMI 1.0 data already provide a reasonable TP performance. What would be the benefit of a 3 to 4 seconds improvement in st.dev.?

In the context of the SARA concept this could reduce the percentage of flights that require two, instead of one, speed/route instructions to stay within the +/- 30 second delivery accuracy at the IAF with 10 to 20%[1]. We think this is sufficient to justify the relatively small effort required for implementation. During the SARA trials the prototype 0 concept was used.

What are the benefits of the prototype 2 concept over prototype 0 concept? The main benefits of concept 2 over concept 0 , apart from the small performance difference, is the availability of a fully populated 4D meteo grid 24 hours each day. In prototype 0 the number of measurements available to populate the grid is directly related to the number of Mode-S observations. This will be limited during hours and in areas with low traffic density. Another important argument to choose for the prototype 2 concept is that it uses additional meteorological information and therefore does not fully depend on the measurements, which may contain unpredictable errors.

Also, in the prototype 2 concept the responsibility for Meteo data quality remains at KNMI, where it legally belongs. Implementation of the prototype 2 concept also opens a way to further improvement of the KNMI meteodata services, which was an important goal for KNMI in this project.

Boeing and KLM are in the process of establishing a launch of the METS Uplink as a service. Significant savings due to improvement of flight efficiency both in cruise and descent are expected.

The results presented in chapter 2.3.2 indicate a significant positive effect of the METS uplink on the SARA operation. The currently available data are insufficient to explain this effect and further analysis is therefore required. In a future operational SARA trial the effect of the use of METS uplink should be taken into account.

[1] The number of flights with abs(ETA-ATA@IAF)>30 sec, decreases with 20% from case 2 to case 3.

4 Further work

4.1 Further analysis

Because the KNMI weather models are aiming at the weather forecast for 12 to 48 hours ahead and the time-horizon of trajectory prediction is much closer, one may question if the performance improvement of prototype 2 versus prototype 0, holds under all weather conditions. At LVNL it was suggested that pt0 concept might be favorable under changeable weather conditions, although at KNMI it is observed that two cases with convective weather showed improved forecast quality when additional ModeS data are assimilated.
Collection of a new set of flights for such an analysis is a labor intensive job and the expected benefit is small. Therefore this should first be verified by measuring the performance of both prototypes over various subsets of the test dataset, representing different weather conditions.

The cause of the bias in ETA-ATA@IAF of 4 to 5 seconds is still unclear. Further detailed analysis might solve this.

Further analysis of the effect of METS uplink shall be supported by analysis of FOQA data. The effect of METS uplink on flight efficiency is of interest to Boeing and KLM. The effect of the combination of METS and SARA is of interest to all parties. If a new operational SARA trial is planned, analysis of this effect shall be taken into account.

4.2 Additional improvement possibilities

There are various options for further improvement. Some are on the KNMI side, others at LVNL.

KNMI is still working on improvement of the assimilation process. The scaling factor of the current models could be changed, such that more detail in the models is allowed. Experiments in that area are ongoing. In the future the resolution of the KNMI weather models might be improved if more processing power becomes available. KNMI is also considering the use of additional data sources, like weather radar and GPS derived data.

At LVNL it is foreseen to enlarge the area from which EHS data are collected, through the use of ARTAS, the surveillance multi-sensor fusion system. ARTAS processes data from about 10 Mode-S radars in the Netherlands, Belgium, Germany and France. Especially extension of the EHS coverage area to the West might yield better results, because quite often our weather is coming from that direction. KNMI indicated that the Mode-S update frequency of 4 seconds, as provided by TAR-4 is sufficient, but a lower frequency, e.g. 20 seconds, will disable the effect of smoothing in the preprocessing.

4.3 Possible implementation phasing

At LVNL it is proposed to start an implementation project for TP-Next generation plus TP-Meteo Server. The current AAA TP would have to be modified to interface with TP-Meteo Server and implementation of TP-MS only would not yield significant benefits, while for SARA implementation the TP-NG concept is required. Therefore

the implementation of these functions will be combined.
Most of the effort for this project will go into TP implementation. TP-MS implementation is a relatively small subtask. The current proposed planning is aiming at mid 2011 for putting into service.
The timing of the implementation at LVNL can be made independent of the implementation at KNMI, if initially a moderate performance target would be accepted.

First the interface between KNMI and LVNL shall be defined (currently grib2ascii as defined in ref 8) in a flexible way, such that future improvements in the data do not require significant interface changes.
Implementation of the prototype 1 concept could provide an acceptable TP performance. It is however expected that especially in changeable weather conditions the prototype 2 concept yields an improved performance. Therefore implementation of this concept remains desirable.

If KNMI decides to implement the use of EHS as a data source in their production environment, it will require little adaptation in the KNMI-LVNL interface. The change from concept 1 implementation to concept 2 implementation is a small effort for LVNL. The main task for that is to ensure operational availability of EHS data (from ARTAS) to KNMI.

5 Conclusions and recommendations

We can conclude the following:

- EHS derived meteo data is a meteo data source of good quality if correct pre-processing is performed.
- Of the different concepts taken into account, the prototype 2 concept provides the best TP performance
- This performance is sufficient to support the SARA concept
- Implementation of this concept can be done by KNMI and LVNL without strong planning dependencies if the KNMI-LVNL interface is defined in a flexible way.
- The combined effect of SARA and Boeing Mets uplink function seems significant, although further evidence is required to confirm this.
- The Mets uplink trial results are sufficient evidence to continue further co-operation and development.

We recommend:

- To start implementation of the TP-Meteo Server concept in LVNL in conjunction with TP-Next Gen development. In that context LVNL should:
    - Agree on a common implementation planning with KNMI
    - Adapt the current formal agreements with KNMI to include delivery of Mode-S EHS data and reception of GRIB-M11 type of data.
    - Investigate the possibilities to extend the Mode-S EHS coverage area with sufficient update rate.
    - Promote the TP-MS concept in FABEC and Eurocontrol.
- KNMI should plan to provide the M11 product as part of their standard services
- A report from Boeing or KLM on the effect of METS on the airborne trajectory predictability would be valuable in the context of SARA implementation.

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