Sequencing Strategies for a Japanese Arrival Flow. Preliminary results.

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[Abstract] We analyze the metering delays of the major Japanese arrival flow. Currently, aircraft are metered at the gate between an en-route sector and the terminal airspace. This creates high controller workload and fuel inefficient trajectories. In a future 'arrival traffic synchronization' concept, arrivals are sequenced en-route in order to avoid peaks in the demand of runways. The main argument for pursuing this approach is that there is few crossing traffic on arrival flows to Tokyo International airport. This paper takes the view of a 'traffic management coordinator' who monitors the flows over several sectors or centers, and who can coordinate actions, such as speed control decisions, with the corresponding controllers. We first summarize that in our data, the metering delays are rather generated by fluctuations in the arrival rate, than by 'peak-hours', and that we found a good correspondence between a simple queueing model and the observed metering delays. We then present initial results of en-route sequencing strategies that reduce the metering delays at the current gate and allow to control them among several flows. This is important for one particular Japanese flow, which is characterized by short en-route times, and thus, limitations of speed control.

I. Introduction

THE current practice in Japanese Air Traffic Flow Management (ATFM) is to attribute ground delays only when they are larger than 10 minutes. Lower delays have to be absorbed during the en-route phase by speed adjustments and radar vectors. The reason for this rule is that weather impact or competition for punctual arrival leave uncertainties in the estimated times of arrival of the aircraft. Its drawback is that large delays and high controller workload may occur in the airspace surrounding the metropolitan airports, which are the major sources of congestion in Japanese airspace[1].

The next step in Japanese ATFM is 'arrival traffic synchronization'[2]. This is a tactical flow operation, enabling trajectory control beyond the sector or even center-boundaries. The key idea is that more accurate trajectory predictions will allow to compute the times at which aircraft should cross certain waypoints, such that imbalances between runway capacity and demand are reduced. This widens the planning horizon of both, air traffic control and ATFM, so that in the long-term, the three components of ICAO's Global ATM Concept 'demand/capacity balancing', 'traffic synchronization' and 'conflict management' are expected to converge[3]. In this context, new strategies to sequence and merge arrival flows are needed[4,5].

Current tools to assist flow managers in this task are the Traffic Management Advisor (TMA)[6] or the Japanese radar data processing system (RDP, which is poorly documented). They typically calculate traffic sequences to the gates between the en-route and terminal airspace, and the delays that are necessary to keep the aircraft equally spaced. These tools are also improved, for example by better controller advisories[7], or larger management horizons[8,9]. But their drawback is that they do not guarantee that their calculations are applicable. For example, how much airspace is necessary to absorb the predicted delays ? Or what is the maximum delay that such a tool predicts ?

The aim of our research is to answer such questions. We analyze flight plan and radar data and develop models to identify new strategies against airspace congestion. In this paper, we report results from an analysis of the major Japanese arrival flow. It has a larger horizon than the current arrival management tools allow to handle, but also a simpler structure than many of the European and American traffic flows (please see below for more details). The paper contains three parts: a queueing analysis, preliminary sequencing strategies under uncertainties, and our ideas for future work.

II. Queueing Analysis

In this section we report our main results from a delay analysis of the major Japanese arrival flow. Details of the analysis can be found in References 10,11. We review quickly the problem description and summarize then our results.

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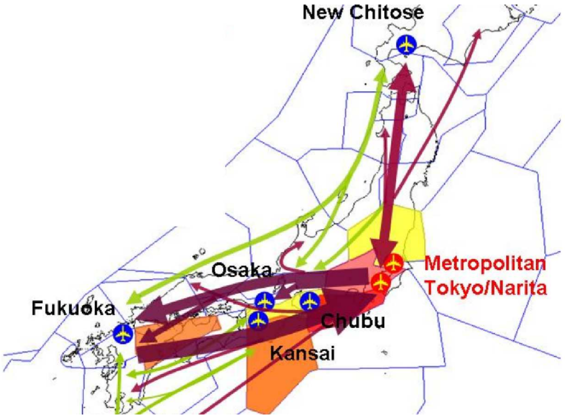

Figure 1. Major Japanese traffic flows.

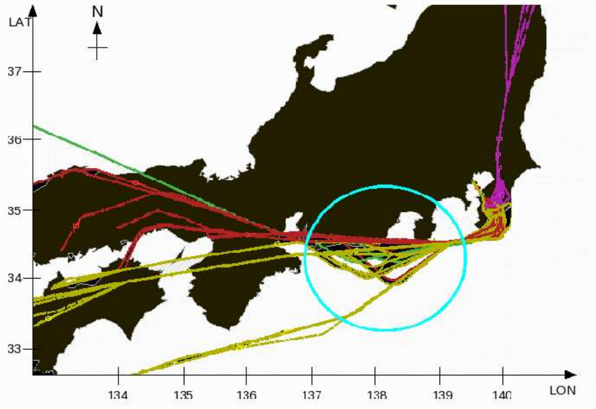

Figure 2. Lateral inefficiencies of the East-bound flow.

At Tokyo Int'l Airport, which is one of the busiest airports in Asia, traffic enters the approach area through three gates; one from the South, one from the West and one from the North. On a normal day about 450 flights arrive at the airport, 70% from the South and the West, and 30 % from the North. Usually, one runway is available exclusively for landings. The two main reasons for arrival delays are:

- Metering constraints at the entry gates
- Merging of flows inside the approach area

In order to protect the approach area from congestion, aircraft are separated by 10 NM on the West and North gates, and 20 NM on the South gate. This is larger than the usual 5 NM radar minimal separation, so delays have to be expected. In the remainder we call such delays *metering delays*. Once the aircraft entered the terminal area, the three flows are merged into one. Delays may occur here, as well.

The major flows in Japanese airspace can be seen in Figure 1. Traffic between Tokyo and Fukuoka (South), Central Japan (Chubu, Kansai, Osaka) and New Chitose (North) make the largest volume (red arrows). The green arrows represent the remaining flows. One can see that there is a crossing between the major and minor routes close to Osaka. Together with the fact that the flows to Tokyo have high priority in terms of punctuality, this crossing is not a critical issue for the remainder of our study. The inefficiencies due to the metering constraint can be seen in Figure 2. It shows the major arrival flows to Tokyo Int'l airport. The colors represent the origins of the arriving aircraft, classified into three regions: red: Central Japan (Osaka area and Western Honshu), yellow: South Japan (Kyushu Island), green: International flights (China, Korea), pink: Northern Japan. The area inside the cyan circle belongs to the en-route sector T09. Aircraft enter T09 from the West, and are visibly deviated from their shortest paths. After leaving the sector, they turn left towards the final approach. Again, delays may occur because of merging the flow from the North.

A. Data Analysis

We analyzed delays at the West gate because it creates the highest metering delays. The West gate lies inside the en-route sector T09, belonging to the Tokyo Area Control Center. The size of T09 is approximately 150 NM x 60 NM. On a typical day, about 450 aircraft per day enter it, and about 290 of them are arrivals to Tokyo Int'l Airport. The main tasks for the controllers in T09 are to meter the aircraft at the gate, and to supervise the crossing of the other ones.

Aircraft with destination to Tokyo Int'l airport enter the sector on six different routes and leave it at the metering point, which is located at the boundary between the en-route airspace and the terminal area (Figure 2). The top of descent (tod) lies inside T09. For a typical day, the inflow rate is about 0.32 aircraft per minute, mostly by aircraft from Central and South Japan. The capacity at the metering point is given by a $s_m = 10$ NM spacing requirement. With an average ground speed of the flow at the gate of $\bar{v}_m = 363\ kt$, this translates into a capacity of $\mu = \bar{v}_m / s_m = 0.61$ (ac/min).

Figure 3 shows the flow (number of flights per 5 minutes) at the metering point between 7:30 and 21:00 for a typical day. We selected 10 days where no high delays or exceptional events were reported. The green bars are from the flight plans, the red ones from the radar data. One can see a fluctuating demand, with slightly higher periods in the morning and evening hours. The pointed horizontal line is the daily average arrival rate ~ 0.3 (ac/min). It is almost the same for the planned and the realized flights. The dotted horizontal curve is the hourly rate, obtained by a moving average. It fluctuates around the daily average with no clear visible peaks. The bold horizontal line is the capacity at the metering point. While the flight plans sometimes exceed the capacity, the radar data generally lies below it.

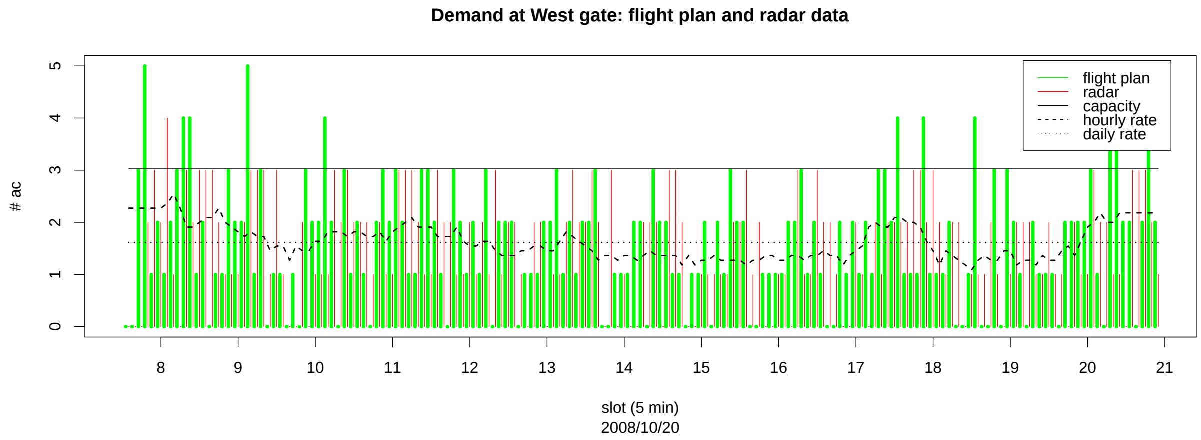

Figure 3. Planned and observed flights. (Source: Reference 11).

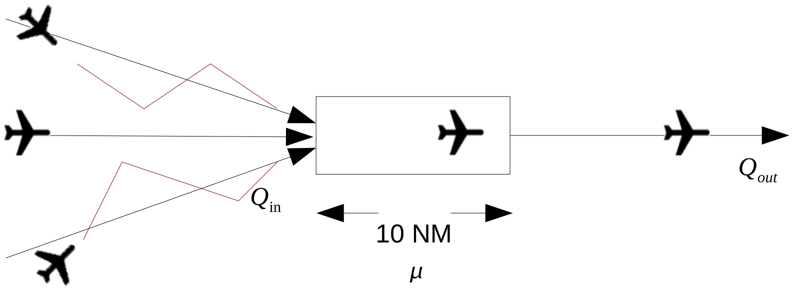

Figure 4. Queuing model of a metering point.

Peak-hours, where demand clearly exceeds capacity, are not visible. So, our conclusions were that the main causes for delays in our data are spontaneous traffic peaks. This confirmed the intuition that, despite changing wind conditions and fleet mixes, the traffic density is a major delay driver.

B. Delay Analysis

Figure 3 showed that the arrival rate and capacity do not vary a lot during the day. A reason for this regular traffic is the strong slot policy at Tokyo International airport. This suggested that the reason why metering delays occur at all, are spontaneous traffic peaks. Our idea was thus to interpret the metering gate as a stochastic stationary queueing system (Figure 4). Input to the system are the flows from the six different routes through T09 with rates (Q^i_{in} (ac/min), $1 \leq i \leq 6$). Output is a single flow, separated by at least s_m =10 NM, which translates into the capacity $\mu = \bar{v}_m / s_m$ (ac/min), given the average ground speed at the gate $\bar{v}_m$. The red lines indicate radar vectors, as a means to absorb metering delays (additional to speed control). We expected from the analysis to better understand how metering delays are generated.

1. Delay Distribution

Aircraft enter the sector T09 on six different routes, and on various altitudes between FL 200 and FL 410. Given the numerous factors that disturb aircraft from their nominal trajectories, we expected that fixed numbers of aircraft enter the sector in an 'arbitrary' order. At the gate, aircraft are metered by a 10 NM rule. Depending on the aircraft speed, the wind conditions and other factors, this spacing may vary from time to time. Natural candidates for our queueing models were thus Poisson arrivals with either general or deterministic service (M/G/1, M/D/1 in Kendall's notation). For both models, the equilibrium distributions of the delays are not directly available, so we decided to simulate the models and compare the distributions with the empirical delay distribution, obtained from the radar data.

The results can be seen in Figure 5. It shows the histogram of the empirical delays, and the simulated delay-in-queue distributions of the queueing models. For each flight, we extracted its traversal time of T09, and, depending on

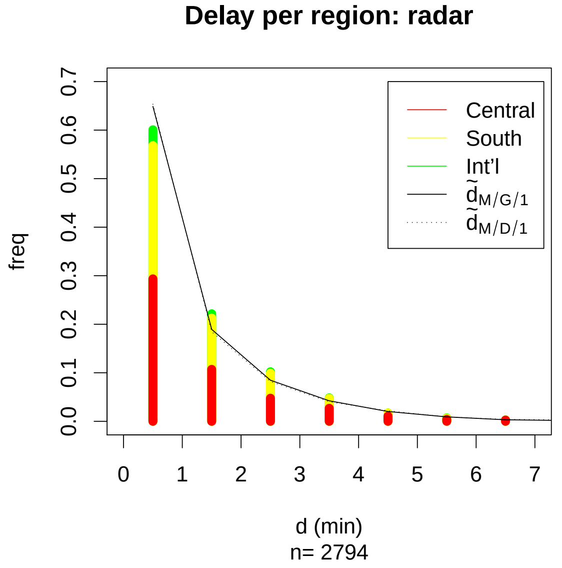

Figure 5. Observed and theoretical metering delays. (Source: 10).

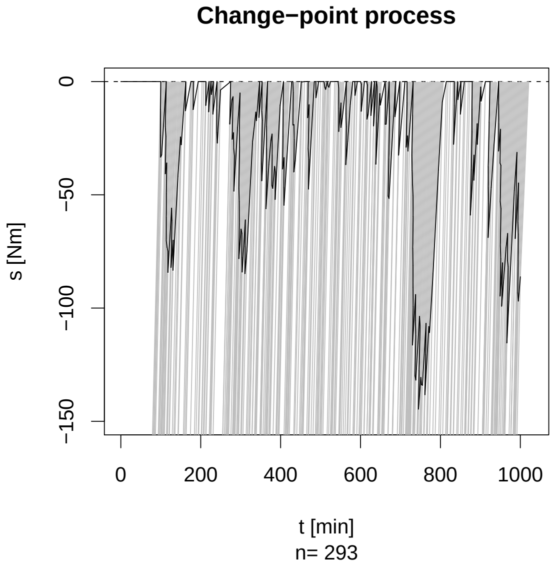

Figure 6. Sample path of a change-point process. (Source: 11).

its route, subtracted a nominal sector crossing time, obtained from flights on the same route under no congested conditions. The colors represent the fraction of aircraft from the corresponding flows with a given delay. The distribution drops sharply with increasing delays. Flows from the Center (red) and South Japan (yellow) have delays in similar proportions, but not exactly the same[10]. International flights account for about 5 % of the flights. The black line is the simulated equilibrium delay distribution of a queuing model with Markovian arrival at rate 0.32 (ac/min) and a service distribution that was sampled from the radar data (M/G/1). The sampled distribution had an average spacing between successive aircraft of 1.64 min with the majority of its density in the interval between 1.5 and 2.0 min. The dotted black line is the simulation of a queue with the same arrival process, but with a deterministic service at 10 NM (0.61 ac/min), based on the average ground speed at the gate (M/D/1). The difference between the two distributions is almost invisible. Both models have virtually the same output: they slightly under-predict the observed delays, except the smallest ones. One reason why the data differs from the theoretical models seems to be that due to the sector geometry, aircraft on northern routes can absorb higher metering delays than those entering from the southern routes. Indeed, we found a weak pattern in favor of this explanation in the radar data[10], but we currently validate it. The average metering delay in the radar data was 1.0 minutes and in the queueing models about 0.95 minutes. Since theoretical delays are the minimal delays, observing that the radar delay is about 5 % higher than the queueing delay was not surprising, which is the second reason for the the difference between data and models.

To validate the models, we compared the number of arrivals in time intervals of 5 minutes with a Poisson distribution and found acceptable goodness-of-fit (measured with a χ^2 test). This was what we expected, since there are many uncertainty factors that act on the individual aircraft, letting them arrive in an ‘arbitrary’ order at the sector entry. A bias due to the 5 NM minimum separation was not visible, because aircraft enter the sector on altitudes between flight levels 200 and 410. On the other hand, two or more aircraft may enter the sector simultaneously, which would provoke a conflict with the assumptions of a Poisson process. As far as the metering constraint is concerned, the observed 1.64 minutes average spacing at the gate match the theoretical 1.639 min, based on the 10 NM constraint and the average ground speed.

2. *Required Airspace for Speed Control*

Based on the above, we analyzed the size of the airspace that is necessary to absorb metering delays during the cruise phase instead of the descent phase. Speed control is probably the simplest and most fuel efficient strategy to absorb en-route delays, creating low additional workload for controllers and the crew. We defined a ‘change-point’ c_i (NM) to be the distance from the sector entry, at which aircraft i would reduce its speed, in order to absorb a metering delay and to keep the minimum separation of 5 NM to its leading aircraft. Given a sequence of aircraft $A_1, A_2, \ldots, A_n$, the question was to understand how the change-point process $c_i,\ i = 1, 2, \ldots, n$ would behave under various traffic patterns. For example, what is the risk that this process grows without limit?Or where are the regions with the largest proportion of speed changes? In Reference 11 we found that the delay that is imposed on an aircraft because a leading aircraft reduces its cruise speed, is equivalent to its metering delay. Thus, the mechanisms generating the metering delays and the one generating the change-points are related. Since speed reductions depend on the cruise speed, atmospheric conditions, aircraft type, etc., we simulated arrival flows, varying the distributions of initial spacings between aircraft and the cruise speeds. The rule was that an aircraft i flies at cruise speed until its change-point, and reduces its speed then by a factor k_i. When the speed of the aircraft was faster than its leading aircraft, we set k_i to a maximal allowable speed reduction (e.g. 10%). In the other case, we set k_i such that the aircraft i adapted its speed to the reduced speed of the leading one.

The right part of Figure 6 shows a typical result for $n = 293$ trajectories. Time is on the horizontal axis, distance to the sector entry on the vertical axis. The black line connects the change-points c_i. They jump up and down in an irregular fashion. Our current results indicate that the highest change-points lie between 100 and 150 NM from the sector entry. Their distribution drops sharply with increasing distance. But there are also a few exceptions, going up to 180 NM. These exceptions need more attention before inferring any conclusions on the real airspace. What was interesting to see was that the mechanism of the change-point process is similar to a certain random walk, because it has the same structure than a general queueing process[12]. As a consequence, we could conclude that the the change-points will not grow without limit, because the average arrival rate is smaller than the capacity.

Our main conclusions from the delay analysis were that (i) a simple queueing model captures the main characteristics of the observed metering delays and (ii) that the evolution of the distance that is necessary to absorb metering delays during cruise phase can be described as a random walk.

III. Sequencing Strategies

Future arrival management will identify the times, at which aircraft should cross certain points in the airspace, such that the flows become more regular. ICAO calls this concept ‘traffic synchronization’[3]. The background is that trajectory-based operations are expected to reduce the uncertainty of the positions of all aircraft, such that the traffic can be controlled beyond the sector, or even center-boundaries.

In our case, there are three major arrival flows to the West gate of Tokyo Int’l airport; one from Central Japan, one from South Japan and one from International, such as China and South Korea. Controllers currently sequence the aircraft manually to the gate between the en-route and terminal airspace with a 10 NM separation constraint. This practice creates radar vectors and high controller workload. In the concept of arrival synchronization, metering points will rather be in en-route airspace than at the gates to the terminal airspace[4,5]. The metering delays will be absorbed during the cruise phase instead of the descent phase. The expected benefits are improved fuel efficiency and reduced controller workload. A reason why this technique is promising for the East-bound arrival flow is that it has few crossings along the route. This means that the impact, such as the generation of secondary conflicts, of en-route speed control on the remaining aircraft is limited. On the other hand, the flow from Central Japan has an en-route time of about 30 minutes in average. This means that the possibility for speed control is limited for this flow.

Two questions to address are thus (i) how much airspace will be required to absorb metering delays during the cruise phase ? And (ii) is this amount of airspace controllable by suitable metering strategies ? In order to answer these questions, we created three models with different numbers of en-route metering points. Our hypothesis was that flows from South and International can absorb their delays by speed control during the cruise-phase, but that the flow from Central Japan has too short en-route times for a simple speed control. The models can be seen in Figure 7. The box corresponds to a sector, arrows to flows. The filled circles are new metering points. The empty circle is the current metering point. The models were:

1. **Central** (one metering point): all traffic is sequenced at the sector entry.
   Advantage: fair and simple
   Disadvantage: limited airspace for flow from Central Japan

2. **Parallel** (three metering points): the flows are sequenced at three independent metering points.
   Advantage: adapts to airspace topology
   Disadvantage: prioritizes flows

3. **Sequential** (two sequential metering points): traffic from South and International is sequenced at the sector entry. The flow from Central Japan is sequenced at the exit.
   Advantage: compromise of first and second strategy
   Disadvantage: flows from South and International are metered twice

The purpose of these models is to reduce the delays at the current gate. They will differ in the delays generated in the upstream sectors. The total delay will not be reduced. Using the queueing results of the previous section, we simulated the metering delays for the three models. In general, the input to the metering points was selected to be Poisson with parameters estimated from the radar data. The service was always deterministic s_{mi} NM for metering point i, which was translated into time unit by the average ground speed of the corresponding flow. The models were thus M/D/1 in Kendall’s notation except for the sequential model, where the input to the second metering point is

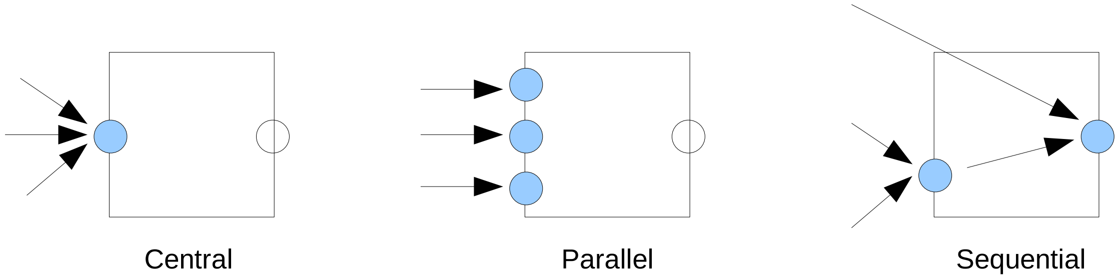

Figure 7. Sequencing strategies: Central (left), Parallel (middle), Sequential (right).

Table 1. Required airspace for speed control (preliminary results).

Model	Origin	s_m (NM)	$\bar{w}$ (min)	w_{max} (min)	$\bar{s}$ (NM)	s_{max} (NM)
current	All	10	0.95	3.5	x	x
1	Central	10	0.7	2.5	53.3	181.5
	Else	10	0.7	1.5	51.9	114.1
2	Central	15	0.7	1.5	52.6	108.9
	Else	25	1.7	4.5	131.7	342.2
3a	Central	10	0.8	2.5	x	x
	Else	25	1.7	4.5	128.5	342.2
3b	Central	10	0.9	2.5	x	x
	Else	20	1.1	3.5	83.5	266.2

the merged flow between the output of the first and the arrivals from Central Japan. This flow has no exponentially distributed inter-arrival times any more. As a simplification for all models, we joined the flows from South Japan and International into one since the flow from International represents only 5% of the total flow. We repeated the simulations several times, and report the results of a typical run.

Table 1 shows the average and maximum delays (columns 4,5) and corresponding airspace that is necessary to absorb the delays by a 10 % speed reduction (columns 6,7). As a reference, the first row contains the current delays, which are roughly the same for the two flows. They are 0.95 minutes in average with a maximum of 3.5 minutes. Currently, metering delays are absorbed by vectors. This is why we used the letter 'x' in the columns for speed control.

In model 1 we used a 10 NM separation constraint at the sector entry (column 3). The ground speed at the sector entry is about 30 % higher than at the exit. As a consequence, model 1 generates only 0.7 minutes of average delay for the flow from Central Japan. The required airspace to absorb the average delays for both flows is about 50 NM. In the worst case, it is 181.5 NM for the flow from Central Japan, and 114 NM for the flow from South and International. The resulting flow through T09 has minimum separation of 10 NM, measured at cruise speed. During the descent the aircraft reduce their speed by about 30 %. We simulated that this implies metering delays at the sector exit of 0.39 minutes in average, which is less than the today's 0.95 minutes.

In model 2, the flows were sequenced independently from each other at the sector entry. We selected 15 NM for the flow from Central Japan and 25 NM for the other one because the output of both resulted in approximately 10 NM separation (more formally the rule was to find all s_{m_i} such that $\sum_j \bar{v}_j/s_{m_i} \approx \bar{v}/s_{m_0}$, where $\bar{v}_j$ is the average ground speed of flow j at the metering point i and s_{m_0} the current metering constraint (10 NM)). Compared to model 1 one can see that the flow from Central Japan has only a maximum of 1.5 minutes (which was 2.5 minutes before), with corresponding airspace of 108.9 NM, almost the half than in model 1. This reduction comes with an increase of the average and maximal delay of the other flow: the average increases from 0.7 to 1.7 min and the worst case from 1.5 min to 4.5 min, with corresponding 342.2 NM required airspace. This approaches the limits of the airspace of the second flow. As in model 1, we simulated the delays in T09, when the flow reduces its speed to 380 kt. These were 0.35 minutes in average.

Finally, model 3a regulates the flow from South and International at the sector entry and keeps the flow from Central Japan metered at the sector exit. In this case, we can compare the delay directly with the current ones, it is still lower (0.8 min vs. 0.7 min). These delays are thought to be absorbed by vectors, so the last two columns are filled with the letter 'x'. Another interesting effect can be seen in model 3b. A reduction of the metering rate from 25 NM to 20 NM reduced the average delays for flow 2 by 64 % but increased them for flow 1 only by 12.5 %. We currently analyze in more detail the reasons for this effect.

At this time of writing, we conclude that the models show the intended effects: (i) the metering delays at the current gate are reduced and (ii) the necessary airspace to absorb delays for the flow from Central Japan is controllable.

But these results show just the general trends. We selected the metering parameters ad-hoc, such that the resulting flows have an average separation of 10 NM. And also the three models are simplifications of the reality: for example the flows are not independent from each other, because they share the same routes. These dependencies may add additional delays. We currently analyze the relationship between the flow rates, metering constraints and delay distributions in more detail.

IV. Conclusions

In this paper we analyzed the metering delays of the largest Japanese arrival flow. Currently, aircraft are metered at the gate between an en-route sector and the terminal airspace. This creates high controller workload and fuel inefficient trajectories. We analyzed the problem in view of a future ‘arrival traffic synchronization’ concept, where arrivals are sequenced en-route in order to avoid peaks in the demand of runways. The main argument for pursuing this approach is that there is few crossing traffic on Japan’s major arrival flow to Tokyo International airport. The paper takes the view of a ‘traffic management coordinator’ who monitors the flows over several sectors, or centers, and who can coordinate actions, such as speed control decisions, with the corresponding controllers.

As a background, we first summarized our main results from References 10,11. These were that the metering delays are rather generated by fluctuations in the arrival rate, than by ‘peak-hours’, and a good correspondence between a simple queueing model and the observed delays. We then presented ideas and initial results of en-route sequencing strategies that reduce the metering delays at the current gate and allow to control them among several flows. This is important for one particular Japanese flow, which is characterized by short en-route times, and thus, limitations of speed control.

Our current approach imagines a one-time speed reduction of aircraft during en-route, the simplest form of speed control. The old metering point at the gate to the terminal area serves as a buffer for uncertainties in trajectory prediction. Immediate extensions are: more sophisticated speed control schemes (several points en-route) or explicit treatment of prediction uncertainties. The output of this research is a better understanding of the airspace congestion problem. This is a step towards strategic flow management, including a balance between en-route and ground delays.

Acknowledgments

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References

[1] A. Kimura. ATFM status in Japan. In *4th Global Air Traffic Flow Management Conference. Capetown. South Africa*, 2007.

[2] S. Nagaoka. ENRI’s R&D Long-term Vision. In *Proceedings of the ENRI International Workshop on ATM/CNS (EIWAC). Tokyo. Japan*, 2009.

[3] ICAO. *Global Air Traffic Management Operational Concept*. International Civil Aviation Organization, 2005.

[4] Sesar Consortium. *The ATM Target Concept. D3*. The Sesar Consortium, 2007.

[5] Joint Planning and Development Office. *Concept of Operations for the Next Generation Air Transportation System*. Version 2.0, 2007.

[6] H. N. Swenson, T. Hoang, S. Engelland, D. Vincent, T. Sanders, B. Sanford, and K. Heere. Design and operational evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center. In *1st USA/Europe Air Traffic Management R&D Seminar, Saclay, France*, 1997.

[7] R. Coppenbarger, R. Lanier, and D. Sweet. Design and development of the en route descent advisor (EDA) for conflict-free arrival metering. In *AIAA Guidance, Navigation, and Control Conference and Exhibit. Providence, Rhode Island.*, 2004.

[8] Multi Center Traffic Management Advisor Publication List. *http:// www.aviationsystemsdivision.arc.nasa.gov/ publications/ terminal/ mctma/ index.shtml*.

[9] G. Slater and D. Yang. Dynamic optimization of delay distribution in an uncertain environment. In *Proceedings of AIAA Conference on Guidance, Navigation, and Control (GNC2004). Providence, Rhode Island, USA*, 2004.

[10] C. Gwiggner, A. Kimura, and S. Nagaoka. Data and queueing analysis of a Japanese arrival flow. *Proceedings of the Asia-Pacific International Symposium on Aerospace Technology. Gifu, Japan.*, 2009.

[11] C. Gwiggner and S. Nagaoka. On required distances to absorb metering delays. *Proceedings of the 2nd CEAS European Air & Space Conference. Manchester, U.K.*, 2009.

[12] W. Feller. *An Introduction to Probability Theory and Its Applications, Volume 2*. Wiley, 2nd edition, 1970.