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Effects of Satellite- and Voice-Switching-Equipment Transmission Delays on Air Traffic Control Communications

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A five-sector simulation was used to investigate the effects of satellite and voice switching system–related communication delays on air traffic control communications. The anticipated maximum delay specifications of the voice-switching systems at the time of the study were used. Under these delay conditions, nine current controllers worked scenarios based on recordings of actual traffic. Communications workload was varied. More communications blocking (step-ons) occurred under very high workload and satellite delays, but no effects of the anticipated switching-system delays were found.

This study addressed the consequences of air–ground delays acquired through satellite-mediated transmission in conjunction with the current WECO 300 communications system and with an anticipated digital voice switching-and-control system. The consequences of air–ground delays due to the anticipated system were also examined.

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Satellite mediation of en route center voice communications is advantageous because it extends the geographical bounds of the air traffic control (ATC) system into otherwise uncontrolled airspace. It is currently used by the Federal Aviation Administration (FAA) in Alaska and the Caribbean. One disadvantage is the increased time required for the voice signal to travel from its source (controller or pilot) to its destination when a satellite is part of the communications path.

Today's terrestrial communications channels typically include a 225-msec *controller delay* when a controller calls an aircraft and practically no *pilot delay* when a pilot calls the controller. The anticipated maximum delay specifications of the voice switching systems at the time of the study were used; they are not operational system delays. They included a 169-msec controller delay and a 70-msec pilot delay. Satellite transmission requires an additional 260 msec for both controller and pilot messages. The total delays with satellite, then, are 485 msec (current controller delay), 260 msec (current pilot delay), 429 msec (new system controller delay) and 330 msec (new system pilot delay).

These delays consist of two components: setup and propagation. The sender must wait until the setup delay has elapsed before speaking. Any portion of the message uttered before the setup delay has elapsed will not be transmitted, resulting in message clipping. The propagation component refers to message transit time.

Pilots and controllers use half-duplex transmitter-receivers that can be used in either a sending or receiving mode. A push-to-talk switch changes the mode from receiver (default) to transmitter. Thus, for example, pilot messages that arrive while a controller has the push-to-talk switch depressed will not be heard by the controller. Similarly, controller messages that arrive while the pilot is transmitting will not be heard by the pilot. Setup and propagation delays lengthen both the time interval between the push-to-talk switch action and the time before the intended receiver is aware that a message was sent. They thus increase the probability that the intended receiver will also begin to transmit, blocking reception of the message in transit. Such blocking is known as a *step-on*.

Although we know of no previously published experimental studies of step-ons, considerable indirect evidence attests to the severity of the problems step-ons can cause:

1. A step-on was among the identified causes of the worst aviation disaster in history—the collision of two Boeing 747s at Tenerife in 1977 that killed 583 people. In this case, a critical controller message was rendered unintelligible by an interfering simultaneous transmission (Spanish Ministry of Transport and Communications, 1978).

2. Step-ons have resulted in aircraft callsign errors reported anonymously to the Aviation Safety Reporting System (ASRS). Monan (1983) summed up their effects as follows: "Simultaneous transmissions obliterated callsigns, induced misperceptions, blocked transmissions and acknowledgements, and contributed to callsign similarities during all phases of flight operations" (p. 28).

3. Blocked frequency events other than frequency congestion per se caused an

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estimated 15.5% of all aircraft/ATC communication losses reported to the ASRS between July 1990 and September 1991 (Drew, Rosenthal, & Lordo, 1992). In an earlier ASRS study, Morrison and Wright (1989) found blocked and congested ATC frequencies to be among three leading factors predisposing pilot errors.

4. Simultaneous transmissions caused 22 ATC operational errors and deviations and 17 pilot deviations (events in which the required separation between aircraft was not maintained) during 1988 and 1989 (Graeber, 1990). Although these numbers indicate that step-ons caused less than 1% of all operational errors and deviations, step-ons may also have contributed to problems in overlapping categories, such as pilot and controller communication technique, similar-sounding alphanumerics, frequency congestion, and discrete information transfer failure.

The purpose of this experiment was to determine the relation between transmission frequency and delay duration in the production of step-ons, so that knowledgeable decisions can be made about the circumstances under which satellite mediation can be safely used. Any statistically significant increase in step-ons above the number that occur with present equipment without satellite mediation would be considered unacceptable.

METHOD

The experiment was conducted using the real-time ATC simulation facilities at the FAA Technical Center. Nine sessions were scheduled each week for 3 weeks, three sessions on each of 3 days each week. A fourth session was added on 1 day because of equipment problems during the first session of the first day.

Five adjacent en route sectors south of Atlanta were chosen for the simulation. Three were used as test sectors: two high-altitude sectors and a low-altitude sector (for sector descriptions, see Appendix). Two other simulated sectors (nontest sectors) realistically transferred aircraft to and from the test sectors. The five-sector simulation consisted of scenarios constructed from recordings of air traffic in the corresponding actual Atlanta Center sectors.

The experimental conditions simulated pilots contending for a busy communications frequency, with air traffic loads that would produce a range of communications activity. Simulation pilots and controllers sat in different rooms and communicated over microphones activated by push-to-talk switches.

Subjects and Supporting Personnel

Nine current, qualified, Full Performance Level male air traffic controllers participated as subjects over the course of the 3-week simulation. Three participated each week in the test-sector radar controller positions. The subjects normally worked the Atlanta Center airspace containing the sectors corresponding to the simulated sectors.

The 9 subjects were paired with 9 other controllers, also from Atlanta Center,

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who worked at the data controller positions during the simulation sessions. Radar controller–data controller pairings were maintained throughout the experiment. Six additional Atlanta Center controllers participated at the two nontest sectors, 1 at each radar controller position each week. Current or former controllers staffed the nontest sector data positions and an aircraft termination sector.

Thirty trained nonpilot personnel participated in the role of pilots. Seven simulation pilot positions were assigned to each of the two high-altitude sectors; 10 were assigned to the low-altitude sector. Six were assigned to the nontest sectors.

The subjects and their communications were observed by three operations observers—supervisory controllers from Atlanta Center specializing in areas of Atlanta Center airspace other than the one containing the test sectors. Prior to the first simulation session, the operations observers were randomly assigned to the sectors, where they remained throughout the simulation testing.

Design and Counterbalancing

The independent variables in this within-subjects design were delay, communications workload, and sector. Step-ons were the dependent variable.

There were four delay conditions, each of which will be indicated herein by two durations (in msec): the ground-to-air (controller) delay followed by the air-to-ground (pilot) delay. The 225/0 baseline delay condition simulated current non-satellite equipment delays by imposing on the simulation intercom circuitry only a 225-msec controller setup delay. The 169/70 condition simulated delays sufficient to encompass those characteristic of the anticipated communications equipment by imposing a 99-msec controller setup delay and 70-msec controller and pilot propagation delays. The 485/260 condition simulated delays caused by satellite transmission in conjunction with current equipment by providing a 225-msec controller setup delay and 260-msec controller and pilot propagation delays. The 429/330 condition simulated delays caused by satellite transmission in conjunction with the anticipated new equipment by imposing a 99-msec controller setup delay and 330-msec controller and pilot propagation delays.

Communications workload was varied by varying the number of aircraft in the sector. The numbers of aircraft were based on peak hourly workload values obtained from Atlanta Center,[1] averaged to represent numbers of aircraft in the sector during peak 5-min intervals: The 100% reference values for the three test sectors—Dublin, Macon, and Sinca—were 12.0, 10.0, and 12.0, respectively. Three levels of communication workload were developed for the study: Medium

[1]The 100% peak value for a sector is a standard value used at ATC centers to construct training problems. It is the mean of (a) the mean number of aircraft per hour in an 8-hr period chosen from the 37th busiest day in the preceding year, (b) the mean number of aircraft per hour in an 8-hr period chosen from the busiest day of the preceding year, and (c) the mean number of aircraft per hour in an 8-hr period on a day chosen at random from the preceding year.

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load was 70%, high load was 90%, and very high load was 110% of the sector's peak value. The two higher levels were constructed by adding aircraft to the 70% scenario. The resulting mean numbers of aircraft and communications loads in the simulation are shown in Table 1.

The three test sectors were based on Dublin and Macon (high-altitude) and Sinca (low-altitude) sectors at Atlanta Center. These sectors are adjacent to one another and typically require coordination to handle traffic moving among them. Atlanta Center descriptions of these sectors are provided in the Appendix.

Equipment

The processing and peripheral support equipment in the simulation was identical to present en route center equipment. Keyboards, displays, terminals, and printers were all identical to current field equipment. Software was identical to that used in real en route centers for both actual operations and data collection and analysis.

The FAA Technical Center AMECOM communications system was configured to provide intercom communications among controllers and between controllers and simulation pilots. Simulated sector frequencies were not the same as those used at Atlanta Center. Simulation frequencies, which were used realistically to transfer aircraft between sectors, designated the intercom channels connecting the controller and pilot positions.

The AMECOM system was modified to provide the setup and propagation delay effects. The delays were created using Vesta Kozo delay boxes, Model DIG-412 (Tokyo: Shino Vesta Fire Corporation). Values were independently calibrated to within 1 msec each day before the first session.

As in actual ATC communications, when either the controller or a pilot keyed the microphone, others transmitting on the same frequency became inaudible. Thus pilots assigned to the same sector (and communications channel) could receive all of the communications on that channel when their microphones were unkeyed. However, unlike the real world, pilot–pilot step-ons did not result in a distracting squeal and blocking; rather, both pilot voices could be heard by the controller and other pilots in the sector.

TABLE 1
Mean Air Traffic Density and Communications Activity

	Air Traffic Density[a]			*Communications Activity*[b]		
Communications Workload	*Dublin*	*Macon*	*Sinca*	*Dublin*	*Macon*	*Sinca*
Medium	7.37	7.48	7.87	2.02	1.47	2.47
High	10.54	10.49	10.17	2.98	2.18	3.39
Very high	13.70	11.31	13.92	4.12	2.50	3.81

[a]Aircraft per 5-minute interval. [b]Radar-controller microphone keypresses per minute.

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TABLE 2
Sequence of Experimental Conditions

	Session[a]								
Team/Week	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
1	1VH	2H	4M	3VH	1H	1M	4H	2VH	3M
2	2H	1M	3VH	4M	1H	1VH	3H	2M	4VH
3	2M	4VH	3H	1M	4H	1VH	3M	2VH	1H

[a]Each entry represents three observations, one at each sector. Numbers represent delay condition: 1 = 225/0, 2 = 169/70, 3 = 485/260, 4 = 429/330. Letters represent communications workload condition: M = medium, H = high, VH = very high.

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Procedure

The sequence of test conditions is shown in Table 2. Each week, a different controller team, consisting of three radar controller–data controller pairs, participated in sessions corresponding to one row of the table. Three sessions were presented each day, except for a fourth session that was presented on the second day of the third week. This fourth session, which was not in the planned sequence of sessions, incorporated the 169/70 delays at very high communications workload and is not shown in Table 2. Again, this session was added because of equipment problems during the first session. The radar-controller subjects were assigned at random to their first sector, and then rotated after each session from one sector to another according to a prearranged schedule.

The simulated air traffic was to be controlled as in an actual operational environment. The radar controllers were instructed to handle all communications with pilots.

During the simulation, pilots in each sector made scripted calls to the controller through headset microphones. The message content and time of these scripted pilot calls were provided on the appropriate pilot's visual display unit. The pilots were instructed to respond rapidly but to refrain from keying their microphones when another voice could be heard. They controlled the simulation aircraft by entering commands on a keyboard.

Simulation aircraft entering a sector were assigned to the pilot with the fewest aircraft. Pilots in Dublin and Macon (high altitude) were responsible for up to three aircraft simultaneously, whereas those in Sinca (low altitude) were responsible for up to two. Pilots sitting in neighboring seats were assigned to different sectors to reduce visual cues to communications channel use.

Data Collection

Communications were taped from positions in the pilot laboratory and grouped into one of three categories: when a pilot message blocked another pilot message (pilot–pilot step-ons), when a pilot message blocked a controller

message (pilot–controller step-ons), or when a controller message blocked a pilot message (controller–pilot step-ons). However, because of the location from which these records were made, controller communications were recorded following the relevant delay and pilot communications without the delay. For this reason, some pilot calls were heard to arrive first when the controller was in fact the first to transmit. The controller–pilot and pilot–controller step-on categories were accordingly merged.

Operations observers were positioned in front of each test sector, where they observed the radar display and listened to the communications channel used by the radar controller. They classified step-ons according to the number of repeated calls each step-on required. Because the operations observers could not hear pilot messages when the observed controller was transmitting, the step-ons they recorded were limited to controller–pilot step-ons caused by the controller keying the microphone during the reception of a pilot message and pilot–pilot step-ons occurring when the controller's microphone was not keyed.

Following each session, the test-sector radar controllers and operations observers completed questionnaires. These instruments were used to record a variety of subjective impressions of the preceding session, including perceptions of controller stress, attentional load, smoothness of air traffic flow, simulation realism, and other information. In a regression analysis, delay showed no statistically significant effects on the responses to these questions, except for a marginal delay by communications workload interaction ($p = .022$) apparently due to less stress reported in the 485/260 condition at very high load. Stress and attentional load were found to increase significantly with communications workload ($p < .0001$). There were also significant differences in stress ratings associated with differences among sectors, in the controllers' responses but not in the observers' ($p < .0001$). Attentional load was found to differ among sectors ($p = .0005$) but only as rated by the controllers; the observer ratings differed marginally among sectors following corrections for multiple testing ($p = .01$). An item related to stress asked the operations observers to rate any tendency toward overcontrol (i.e., acting too far ahead of the aircraft); the observers reported little tendency to overcontrol during the simulation. No cases of "extensive" overcontrol were reported. Three observations of "some" overcontrol were recorded following sessions with 225/0, 169/70, and 429/330 delays. The remaining 78 observations indicated no tendency to overcontrol.

RESULTS

Pilot–Pilot Step-Ons

Multiple-regression analyses found no statistically significant effects of delay on pilot-pilot step-ons, ($p > .05$) although there was a significant effect of communications workload ($p < .004$). No delay effects were expected because calls made by one pilot were heard by others in the same sector with no delay.

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Controller–Pilot/Pilot–Controller Step-Ons

The regression analysis indicated that there was a statistically significant effect of delay ($p = .001$) and a statistically significant delay by communications workload interaction ($p < .05$). A Tukey HSD analysis was conducted to compare the individual cells. It revealed that there were significantly more controller–pilot/pilot–controller step-ons in either of the very high communications workload satellite-delay conditions than in either of the very high communications workload non–satellite-delay conditions (see Figure 1). At the very high level of communications workload, the addition of the 260-msec satellite delays to the 225/0 baseline delay condition resulted in a 150% increase in controller–pilot step-ons, and when added to the 169/70 delay condition, satellite delays resulted in a 176% increase in this type of step-on.

An initial regression analysis found no statistically significant differences for comparisons at medium and high workload ($p > .25$). A second regression, suggested by the data shown in Figure 1, compared both of the satellite conditions to both of the nonsatellite conditions, and dropped comparisons at very high workload. This procedure, which increased statistical power, led to differences that approached statistical significance at $p = .04$.

Chance-probability values were calculated for all differences between the current (225/0) and anticipated (169/70) digital system delays not involving satellite delays and between the current (485/260) and anticipated (429/330) system delays involving satellite delays. These calculations were made within each communications workload level and sector and overall. There was no suggestion of a significant difference in any of these comparisons.

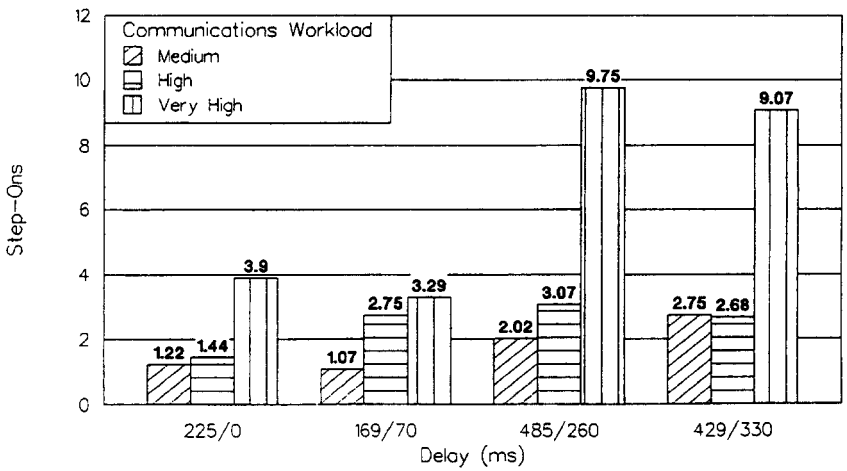

FIGURE 1 Mean step-ons by delay and communications workload.

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Retransmissions

One of the likely impacts of step-ons is the need for the sender to retransmit information which might have been lost due to the step-on. At worst, step-ons can generate retransmissions that would themselves be blocked by step-ons. Three categories of step-on were recorded by the operations observers depending on the number of additional calls made.

The mean numbers of step-ons requiring zero, one, and two additional calls were 1.67, 1.70, and 0.06, respectively, per session and per sector. These results mean that 48.7% required no additional calls and 49.6% of the step-ons required one additional call. Only 1.7% of the step-ons required two additional calls. Thus, a stepped-on message required an average of 0.53 additional calls. However, the number of callbacks required due to blocking during the simulation was probably less than that which would occur in the real world because the simulation did not include blocking during pilot–pilot step-ons.

DISCUSSION

The purpose of this experiment was to determine the relation between communications workload and delay duration in the production of step-ons. Step-ons were found to increase with the delays associated with satellite-mediated communications when combined with the delays characteristic of current equipment or with the maximum delays specified for anticipated voice switching and control systems. These increases were found only when communications workload was very high.

One of the likely impacts of step-ons is the need for the sender to retransmit information. However, the sender often needs to be told about the step-on, because otherwise there may be no indication that the step-on occurred, aside from the eventual failure to act on the information that was lost. At worst, step-ons can generate callbacks that would themselves be blocked by further step-ons.

In the simulation, the absolute number of step-ons was limited due to factors that limited pilot contention, such as the assignment of multiple aircraft per pilot. No sector in any session had more than 0.42 step-ons per minute, but more would be expected with realistic pilot contention for a busy communications frequency. Limitations in the electronic aspects of the simulation (no blocking) reduced loss of information due to pilot–pilot step-ons and thus reduced the number of retransmissions. Therefore, under all delay and communications workload conditions, fewer step-ons and retransmissions would be expected in the simulation than in real-world operations.

Based on these results, areas with very high communications workload should continue to rely on ground-based communications. The Caribbean and Alaskan areas that currently use satellites without known problems never approach the

communication volumes associated with increased step-ons as simulated in this study. However, before satellites are used to mediate communications in any particular airspace, its maximum communications volume and the likelihood of increased step-ons need to be considered.

In addition, the results emphasize the need for programs, such as data-link and standardized taxi-way routing, that are intended to decrease pilot and controller communications. Data-link, for example, employs electronic traffic-control message transmission from ground computers to cockpit displays. This can reduce voice communications load considerably, as shown by simulation studies (for a summary, see Kerns, 1991). These programs are likely to decrease the incidence of step-ons. The results also suggest the need for improved aircraft callsign identification uniqueness, which would mitigate step-on–induced addressee problems (Monan, 1983).

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Mitchell Grossberg is now at the FAA Technical Center.

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APPENDIX

Airspace Simulated

The test sectors were developed from recordings of live air traffic in corresponding sectors described by Atlanta Center as follows (1989). Dublin High and Sinca Low have since been redesignated by Atlanta Center.

Dublin High

Air carrier aircraft generate the majority of traffic handled by this sector. This sector provides Instrument Flight Rules arrival service to the Atlanta terminal area and, at the same time, handles a large amount of en route traffic. A moderate amount of traffic is generated by aircraft transitioning to/from Macon, GA/Robins AFB and adjacent airports. Traffic flow is predominately northwest/southeast with numerous departures from Atlanta and arrivals to the East Coast interspersed with Atlanta area arrivals. The high complexity of this sector is created by Atlanta terminal area arrivals entering the sector at several locations that require spacing while continuing to provide service to en route traffic. A large amount of coordination is required with the Sinca sector in order to achieve the required intrail spacing. The unique characteristic of this sector, which increases the complexity, is the requirement for the controllers to change altitudes of a large percentage of aircraft to conform with letters of agreement and traffic flow. These situations add to the sector's complexity and necessitate careful planning and coordination. This sector daily works F-15 aircraft to/from Robins AFB.

Macon High

This sector provides IFR service from the Atlanta terminal area with a mixture of a proportionate amount of en route traffic. Traffic flow is predominately north/south with a moderate amount of crossing traffic. Military operations generate additional traffic which must be blended with normal traffic. The unique characteristic of this sector is the fact that controllers are required to change altitudes on all J45 traffic. Obviously this built-in head-on situation increases the sector's complexity and necessitates careful planning and coordination.

Sinca Low

This sector provides IFR arrival service to the Atlanta terminal area and, at the same time, handles a proportionate amount of en route traffic. Traffic flow is predominately northwest/southeast. Military operations generate a moderate amount of traffic that must be blended with the traffic flow. Controllers are required to provide arrival spacing for the Atlanta terminal area, which requires careful planning and a large amount of coordination with the Dublin High sector.

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