A High Data Rate Ka Band Global Network For Weather

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ABSTRACT

The United States Air Force Weather operates globally to collect observations of atmospheric conditions. Instruments include human observers, weather satellites, and weather radars. A new era is forthcoming in the domain of weather satellites, as satellite sensors are improved and additional weather satellites are launched by China, Japan, and others. The United States is integrating its civilian and military weather satellites but the Defense Meteorological satellite (DMSP) and national civilian satellites will both continue in use for a decade or more. Sensor improvements in the DMSP will increase the number of optical channels while also increasing sample quantization from 8 to 12 bits. Prior operation emphasized storing imagery and dumping the data from a full orbit at one earth station. A small tactical terminal (STT) has been developed to allow receipt of the satellite real-time downlink at any geographic location. Thus, with a suitably dispersed group of STTs, data can be collected in near real time on a global basis.

Although it may not seem significant, it is highly desirable to retrieve and make use of all satellite data in near real time. An example of the need for timely data is in the case of tropical storms, where timely data can increase warning time in case of a tornado, hurricane or typhoon. Weather touches all lives, but can be of critical importance in military operations. The U.S. Air Force has had an operational requirement for retrieval of global data within 15 minutes.

One best use of the weather satellite data is for initializing the complex computer weather model, which is run several times each day. But due to the magnitude of the data that may be downlinked by a single pass of a weather satellite, transmitting this data back to the Air Force Weather Agency, where it may be used in the model, presents a significant global data communications challenge. This paper describes a Ka Band satellite communications network to accomplish the communications. This is representative of a class of emerging international data communications applications that might be supported by a global Ka Band satellite system. Further, the proliferation of national weather satellites data offers an opportunity to share weather data which might also be accomplished through a global Ka Band satellite communications system. Latency is compared for satellite communications and fiber optic cable relay.

INTRODUCTION

A brief introduction to the concept for globally distributed data collection and retrieval, termed STT-Net, is followed by an outline of the data collected by the U.S. weather satellites in low earth polar orbit to define the amount of data to be retransmitted by Ka Band satellite communications. This is followed by a discussion of Ka Band satellite communications design for this global problem. This leads to analysis of the total latency from satellite sensor to central database in the U.S. or end-to-end latency. Latency associated with fiber optic delivery from one or two polar region sites is compared to latency for satellite communications from STT-Net sites.

SMALL TACTICAL TERMINAL (STT) STTNet FOR DISTRIBUTED DATA COLLECTION

With low altitude orbits, it becomes necessary to retrieve the data at globally distributed points and retransmit it quickly, that is, with low latency, back to a central location for use in modeling and prediction, or selected redistribution. A small tactical terminal (STT) was developed to support local stand alone operations but has been modified to allow block transmission of polar satellite passes to AFWA. Transportable for deployment, the STT is a receive-only system in satellite communications terms.

It is proposed to deploy STTs at carefully selected locations around the globe for local, near real time collection of satellite observation in various regions. Once the data is returned to earth, it may be transmitted to other locations using high speed data communications, such as Ka Band satellite communications. Up to 21 sites would be needed to collect near full earth observations. As few as six sites are under consideration still giving over 35 % of earth coverage in a 24 hr period.

Thus, there are trade-off relationships between the fraction of the globe covered and the number of STT sites; coverage and siting differences among sites in locating an ensemble of sites; the delivery time (latency) as a function of file sizes and data rates (bandwidth) provided by the communications media; cost versus bandwidth and number of sites; the degree of compression appropriate for scientific imaging data (i.e., compression ratio versus the quality of secondary data products derived from compressed satellite data); and latency, availability, reliability, and cost among competing communications media. Some of these trade-offs are briefly discussed to provide a basis for defining an overall network of STT sites and Ka Band terminals and satellites.

STT Siting

Figure 1 summarizes the results of extensive analysis performed by Aerospace Corporation. The figure shows 20 STT weather satellite collection sites. With 8 sites, 41 percent of the earth's surface is covered, meaning that 41 percent of the earth's area is viewed and the observation data returned to an STT in near real time. The 8 sites are located in the islands of Hawaii, Puerto Rico, and Diego Garcia; and on land in Korea, Germany, and Saudi Arabia; and in the United States Nebraska and Arizona. Calculations have been performed with various numbers and specific locations of sites. Analysis shows that for a satellite pass, the area viewed by the sensors covers 11 percent of the earth. Thus at least 9 sites would be needed to cover the earth; but because ideal siting is not available, up to 20 sites have been analyzed. For the particular 20 site case of Figure 1, earth coverage was increased to 87 percent.

WEATHER SATELLITES

Weather Satellite Coverage

Analysis by Aerospace Corporation has identified the time periods of contact for each site, during which the satellite is above 8^o elevation angle, as shown by the coverage patterns on Figure 1. Sample results are given in Table 1 for a few hypothetical ground sites.

This analysis provides the duration of each contact and time of occurrence. The numbers in the last column refer to the number of contacts that exceed 10 minutes duration (numerator)/the total number in 14 days (denominator). Ten minutes has been used for the contact period in this paper.

The initially selected plan is to store the satellite data until the last portion of the pass. As a result the sensor data taken during the early part of the pass is stored longer than the data corresponding to the final portion of the pass. This variable delay or latency is related to the coverage. The coverage weighted-average latency is about 6 minutes (i.e., data for half the coverage is delayed by less than 6 minutes).

Table 1. Weather Satellite Contacts with Distributed Earth Stations

Site	Satellite	Contact Start Time	Contact Stop Time	Contact Duration (Minutes)	No. >10 Minutes
Moscow	TIROS N14	10.31	21.98	11.67	397/600
Falklands	DMSP F13	15.02	25.75	10.73	363/530
Alaska	DMSP F14	27.46	34.67	7.21	491/812
Peru	DMSP F13	28.69	35.93	7.23	213/308
Korea	DMSP F14	38.61	51.80	13.18	271/383
Arizona	DMSP F13	40.13	53.21	13.08	258/347
Nebraska	DMSP F13	42.70	54.39	11.69	280/406

Once received, the data may be processed into the desired format and compressed for retransmission by satellite or other means. Compression is to be employed to reduce latency due to communications. Better compression results are obtained by compressing an entire sensor image file rather than operating on the data stream in real time. This is the rationale for delaying telemetry until the end of the pass, since if it is received earlier, it will not be processed until all data are received.

Weather Satellite Data

In this paper, data collected by sensors carried on weather satellites in low altitude orbits are discussed. The TIROS weather satellite and the Defense Meteorological Satellite both carry sets of sensors, using the visible, infrared (IR) and microwave spectral regions. These sensors produce digital files, if recorded; or may be considered as producing digital data streams analogous to imagery in the visible spectrum. Focal plane detector arrays of 1000 x 1000 pixels are typical with 8-bit resolution. In the near future, the arrays will become larger with bit depth increasing to 12 bits. The volume of data involved will increase due both to enhanced resolution of sensors and to larger numbers of satellites. In this paper, we are concerned only with the STT-Net for receiving downlinks of U.S. weather satellites in low earth orbit. [Sensor data is purchased from international meteorological agencies and may be added to the transmission load when discussing global satellite communications for weather].

Sensor data is recorded over an interval of observation and then transmitted to fixed ground sites; simultaneously the data is also transmitted in near real time. With regard to satellite communications, the received data will be compressed and then retransmitted via Ka Band satellite. Since we have the ability to choose the data rate, we will be interested in the aggregate file size of the data collected from one satellite pass. The aggregate file size is determined for 10 minutes of orbit in Table 2. The numbers are in (8 bit) Bytes. Shorter or longer intervals could also be considered. In current operations, data is recorded for the entire orbit period and then “dumped” (telemetered to the ground) once per orbit. This results both in a reduction of “fine” data that can be provided and in latency of up to 2 hours in the data when it is received at “Weather Central.” STT-Net both provides the fine data and reduces the latency.

KA BAND SATELLITE COMMUNICATIONS SERVICE

Many Commercial systems have been proposed in Ka Band to provide wideband communications on a global scale. Systems vary in uplink data rates and anticipated terminal sizes. For the purpose of discussion, the weather communications may require data rates greater than 2 Mb/s (although we may investigate lower rates for tradeoff comparison). Astrolink and Spaceway which may accept 20 Mb/s uplink rates. Many of the proposed systems are following an Internet model which leads to asymmetrical link rates.

- The weather application is for transmit or uplinking of bulk data with smaller return link data, and thus corresponds to the mirror image of the Internet model (i.e., intermittent requests and bulk downloads), which may be typical of some information age applications.

There appears to be a somewhat broad consensus that a business or corporate terminal will emerge for use in higher data rate and/or high duty cycle applications. Due to the volume of weather data, the business terminal is adapted, rather than the home terminal class, for geostationary (GEO) satellite systems. A military system based on a Ka Band replacement for the 7/8 GHz Defense Satellite Communications System (DSCS) is also compared. The use of the commercial systems is recommended on the basis that these will become available 5 or more years earlier than a military system.

Consideration and analysis must be given to coverage, link design, and the overall network, since multiple satellite hops will increase latency or delay.

Ka Band Satellite Communications Coverage

The GEO systems described in the literature generally have spot beams of less than 1^{o} beamwidth arranged to stare at high traffic zones. As an example, 20 hypothetical STT site locations are plotted on the map in Figure 1. The union of coverage planned for Euroskyway, Atrolink, and Spaceway, as we understand it for 2004, is approximated by the coverage zones about two of the ground sites (i.e., North America and Europe, with some coverge of North Africa and mid-East). This plot reveals that half the sites (Guam, Peru, Falkland and Ascension Islands, Diego Garcia, Singapore, South Africa, and New Zealand) are *not* in the coverage pattern. This suggests:

- It may be highly desirable for satellite designers to plan a scanning beam capable of reaching any point within view. [Such a beam can be sent to unanticipated traffic sources/sinks greatly increasing flexibility. This technique has been demonstrated in the NASA ACTS satellite.]
- It must be assumed that such important sites as Moscow, Seoul, and Saudi Arabia will be contacted by such beams if they are not in the fixed coverage.

The weather satellites have highly regular patterns of contact with STT locations, allowing the communications satellite's scanning beam to be programmed to contact the site at the precise time when the weather data transmission will be needed.

It is proposed to receive the satellite data and retransmit fine imagery, semi-fine imagery, a doc file and a special sensor output file for each pass. These four files total 70.3 Mbytes for a 10 minute pass for DMSP (or 560 megabits).

For TIROS, a 10-minute readout produces a 73.7 Mbyte file [five vis channels AVHRR Imagery at 20,480 Bytes/scan x 6 scans/second x 600 seconds]. The doc file is 1.8 MB and the AIP file 5.8 MB, for a total of 81.3 Mbytes (650 megabits).

Although not critically important to communications, it is interesting to determine the daily data delivery. This is shown in Table 2 for 6 satellites and 6 and 20 ground site cases. The total data for the 20 ground site case is 32 gigabytes (256 gigabits). Since this is the amount of data for a 24-hour period, this is equivalent to a continuous data stream at 2.96 Mb/s. Since there are 20 sites, it follows that the average rate per site is about 150 kb/s, surprisingly small.

Table 2. Weather Data Delivery from Space per Day

	Mbytes/ Pass	Passes/ 6 sites	GBytes/ 6 sites	Passes/ 20 sites	GBytes/ 20 sites
TIROS	81.3	41	3.333	155	12.601
DMSP	70.3	69	4.851	276	19.403

An average file size may be estimated by weighing the file sizes by the number of satellites of each type (2 TIROS, 4 DMSP). This value is 73.96 or 74 Mbytes. Tradeoffs involving compression are briefly discussed in a subsequent section.

The overall problem is to deliver the globally retrieved satellite data within a latency limit. This limit has been arbitrarily chosen to be 15 minutes after pass or average data latency of 25 minutes. The total latency can be considered a variable. The latency is produced by a series of factors, and only certain factors are under control of the satellite communications designer.

Partition of Latency

The latency may be defined as the age of the data from the time it has been measured (by the satellite sensor) to its delivery as a complete file to a server at the destination. The data may be recorded and delayed before transmission to the STT; there is a finite time for transmission to the ground (a function of file size and data rate); there is some ground processing (reformatting and possible compression) before transmission via satellite; there is the finite time for satellite communications; and any time required to complete the delivery via a local area network and processing for ingest into the server. These factors and estimates of their maximum and minimum values listed in the table.

The satellite transmission mode may be ATM, but due to the apparent need for a scanning beam to visit the sites at a scheduled time, we assume continuous availability for transmission during this visit time (no multiple access delay).

Latency Factor	Maximum	Minimum
Satellite Buffer	10 minutes	0 minutes*
Satellite Telemetry	9.6	4.8
Ground Processing	5	~ 1
SATCOM Transmission	x_1	x_2
Delivery / Ingest	3	0*

*Eliminate by interpretation of definition

With x_i as the satellite transmission time, and rounding to whole numbers, the latencies are:

$$\text{Latency (Maximum)} = 28 + x_1$$

$$\text{Latency (Minimum)} = 6 + x_2 \quad (1)$$

Using 70 Mbytes = 560 Mbits as the file size, if x_2 is 6 minutes (360 sec.), the data rate is 1.55 mb/s. Delivery in 3 minutes requires 3.1 mb/s. If the data rate is 512kb/s, the transmission time is 18.2 minutes and the total estimated latency is 24.2 minutes. To meet a total latency of 15 minutes, x_2 is 9 minutes (540 sec.) and the satellite data rate is 1.04 mb/s.

Latency with Fiber Optic Cable

An alternative is to deliver the data from an entire orbit by means of a single data dump at a polar location. Recorder limitations reduce the resolution of data that can be provided; hence this is not a valid comparison. With satellite recording, the buffer time is increased by the orbit period or 90 minutes. Two polar ground stations (north and south) would imply an additional 45 minutes (maximum on orbit storage of half the orbit period).

Under the scenario of dumping the entire orbit's data at one or two polar sites, the data must still be transported back to the central location (Nebraska). Again this might be accomplished by satellite communications (for "dump" sites a latitudes within the GEO coverage). However, we compare the delivery using fiber optic cable. The fiber optic transmission occurs at a velocity less than the speed of light, or c/n, where n is the index of refraction. The transmission time is given by

$$\text{Transmission time (fiber)} = \text{distance or cable length} / (c/n) \qquad (2)$$

Thus the fiber contributes a latency determined by *the total time to transmit the file at the lowest rate encountered over the length of the cable* plus the physical transmission time of the fiber from (2). From such remote locations, the likelihood is that the end-to-end cable will not support high data rates throughout the entire span of the cable. We model the cable run to be comprised of two segments; one limited to 20 mb/s and one at OC-3 (45 mb/s). This implies that the equivalent or effective data rate is the lower rate. The estimated cable length from the north pole is 6,500 miles and from the south pole, 16,000 miles, producing transmission times exceeding 49 msec. and 123 msec., both small compared to other factors. However, the data rate limitation due to the cable available to such locations, is similar to data rate limitations frequently encountered (and termed "the last mile" or "last 400 feet" problem). For the 74 Mbyte file size, under these assumptions, the corresponding *total* latencies accounting for the fiber optic delays and the orbit storage, are:

Dump Recorded Data at:	**Maximum**	**Minimum**
One Polar Dump Site	28 + 15 + 90 = 143 min.	6 + 105 = 111 min.
Dual Polar Dump Sites	28 +15 + 45 = 88 min.	6 + 60 = 66 min.

The use of the polar dump sites is disappointing since the total latencies all exceed an hour and cannot be considered "near real time." In particular, the assumed availability of fiber optic cable does not entirely solve the latency problem, at least for some sites, because end-to-end transmission time is determined by the lowest data rate encountered.

Data Compression

The data returned by the satellites is not entirely equivalent to "imagery." The data are used with algorithms to create what might be termed secondary products, notably predictions of future values (weather). Consequently, the effect of errors in the primary data on the quality of the secondary products is expected to be the limitation in the degree of compression of the data that can be applied to reduce transmission time (i.e., rather than subjective *picture quality* as determined by the eye for television). This subject is under study, and it is expected that the degree of file compression will be much smaller than what has come to be the experience with digital video. While the results are not yet available, it is believed that compression of 25 percent may be possible. This would allow a slightly lower data rate for the same latency, but does not significantly alter the overall performance due to large fixed latency factors.

CONCLUSIONS

A large global data communications application exists for disseminating weather satellite data and associated information products. The low earth orbit portion of this is discussed and totals 32 gigabytes per day. Satellite retransmission of this staggering amount of data can meet latency requirements of minutes when transmitted at < 2mb/s. Comparison with fiber optic cable transmission reveals that latency is lower with satellite communications (for the specific case of two polar dump sites and a central U.S. destination for data), largely due to the latency of on-orbit data storage, and low data rate connection links to high speed fiber access points. This study provides yet another reminder of the importance of the ability to deploy a small satellite terminal (VSAT) directly at end points (of a point-to-point connection), whereas fiber optic cable may not touch arbitrary end points.

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