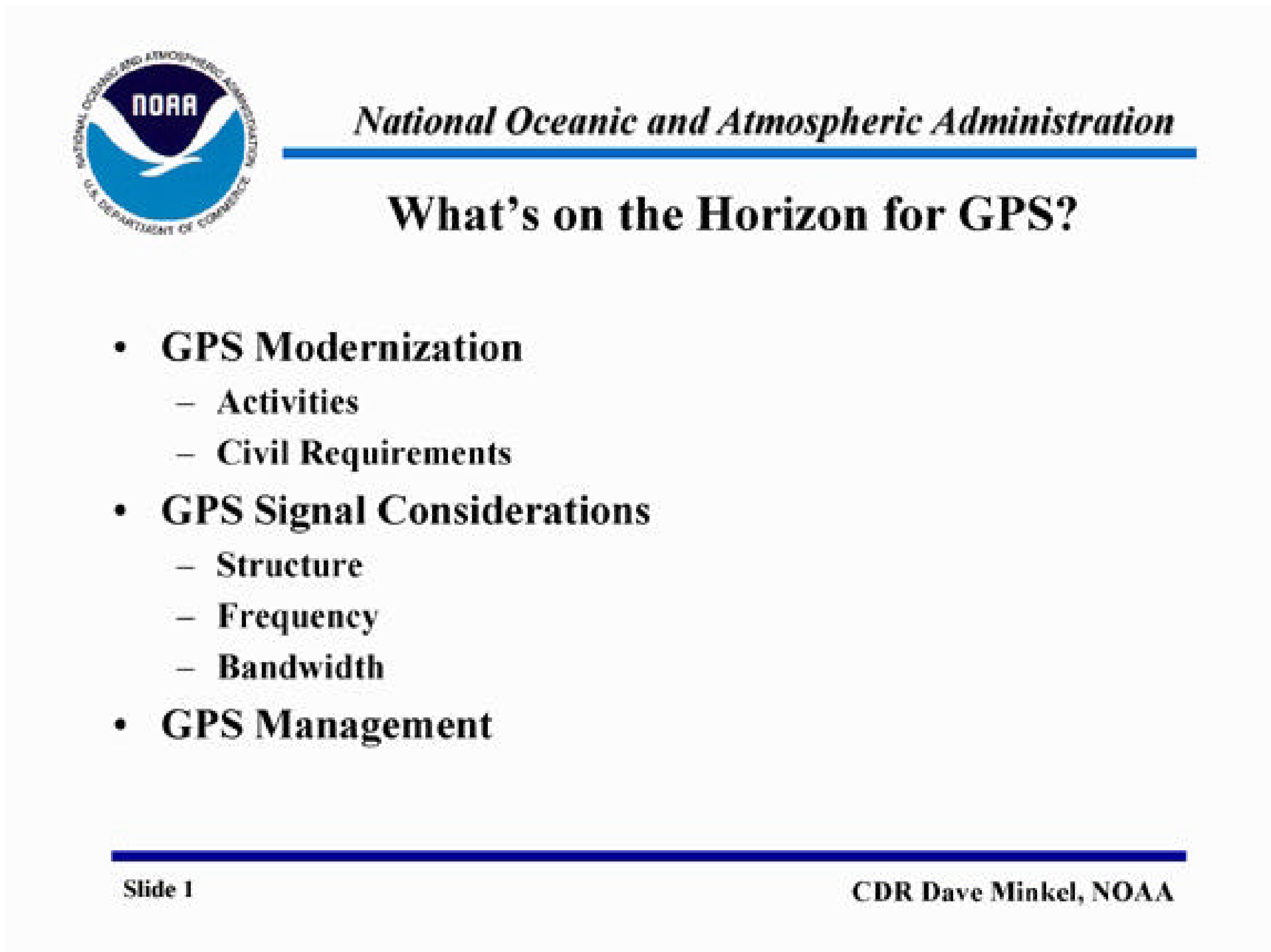
IGS

SESSION 2

FUTURE DIRECTIONS


National Oceanic and Atmospheric Administration
What's on the Horizon for GPS?
• GPS Modernization
– Activities
– Civil Requirements
• GPS Signal Considerations
– Structure
– Frequency
– Bandwidth
• GPS Management
Slide 1
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GPS Modernization Activities

- **IGEB chartered IGEB Steering Group**
  - Responsible for studies to support 2nd and 3rd civil signal decision(s)
  - Met weekly from March until September
- **GPS Modernization Working Group**
  - Civil and Military represented
  - Responsible for studies required for other GPS Modernization decisions
  - Three groups - Navwar, Global Aviation, Everything Else
  - Produced GPS Operational Requirements Document

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GPS Modernization - Reqt.s Summary

	Fewer Users	Most Users
• Coverage		
– Landmass, 6 or more full-time signals in view	Regional	Worldwide ($\pm 70^{\circ}$ Lat)
– Oceans and ice, 4 or more full-time signals in view	Worldwide	Global ($\pm 90^{\circ}$ Lat)
– Space, 3 or more full-time signals in view	GEO	Twice GEO
• Position (2 sigma, H & V)		
– Real-time, unaugmented		
• Oceans	100m	10m
• Landmass, Space	10m	1m
– With differential augmentations		
• Real-time, landmass	1m	0.1m
• Near real-time (minutes),	0.1m	0.01m
• Post-processed (hours)	0.01m	0.001m

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Requirements Summary - Cont.

	Fewer Users	Most Users
• **Frequencies**	2	3
• **Timing**	10ns	1ns
• **Velocity**	1m/s	0.1m/s
• **Service Availability**		
– Oceans	99%	99%
– Landmass	99.9%	99.999%
– Space	100% over 24hrs	
• **Integrity**		
– Monitoring	100%	100%
– Alarm	6s $^{-7}$	1s $^{-9}$
– Per Aircraft Approach	-2x10	-610
• **Continuity**	(1-10)/15sec	(1-2x10)/30sec
• **Protection**		
– Unintentional Interference, Land	+10dB	+20dB
– Jamming, Local Theater (500km)	+20dB	+40dB

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Possible "Solutions"

- Constellation
  - 30 - 30+ satellites
  - Civil MEO augmentation
  - Civil GEO augmentation
  - High-power GEO augmentation
  - High-power MEO constellation
- Aft/side-facing/broad-beam antenna
- RAIM/Integrity Message
- Internal/External augmentation
- Improved time/pseudeorange accuracy
- L_2/L_c configuration

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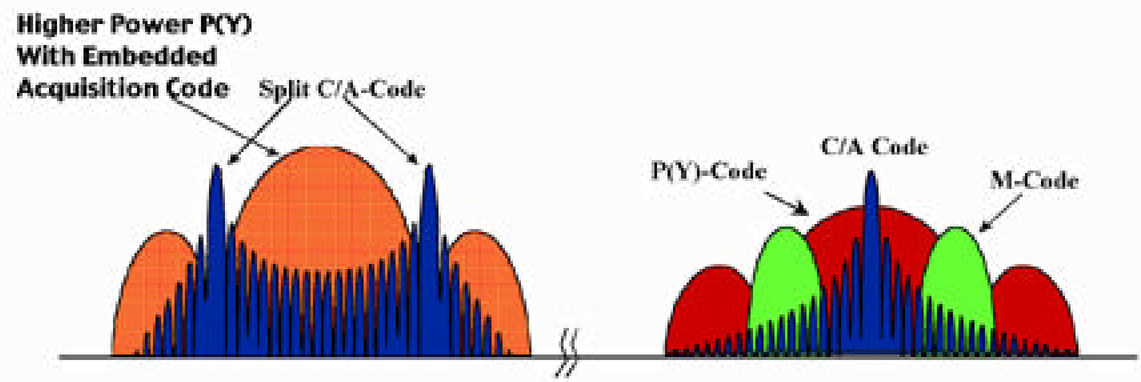
Signal Structures Considered for L2



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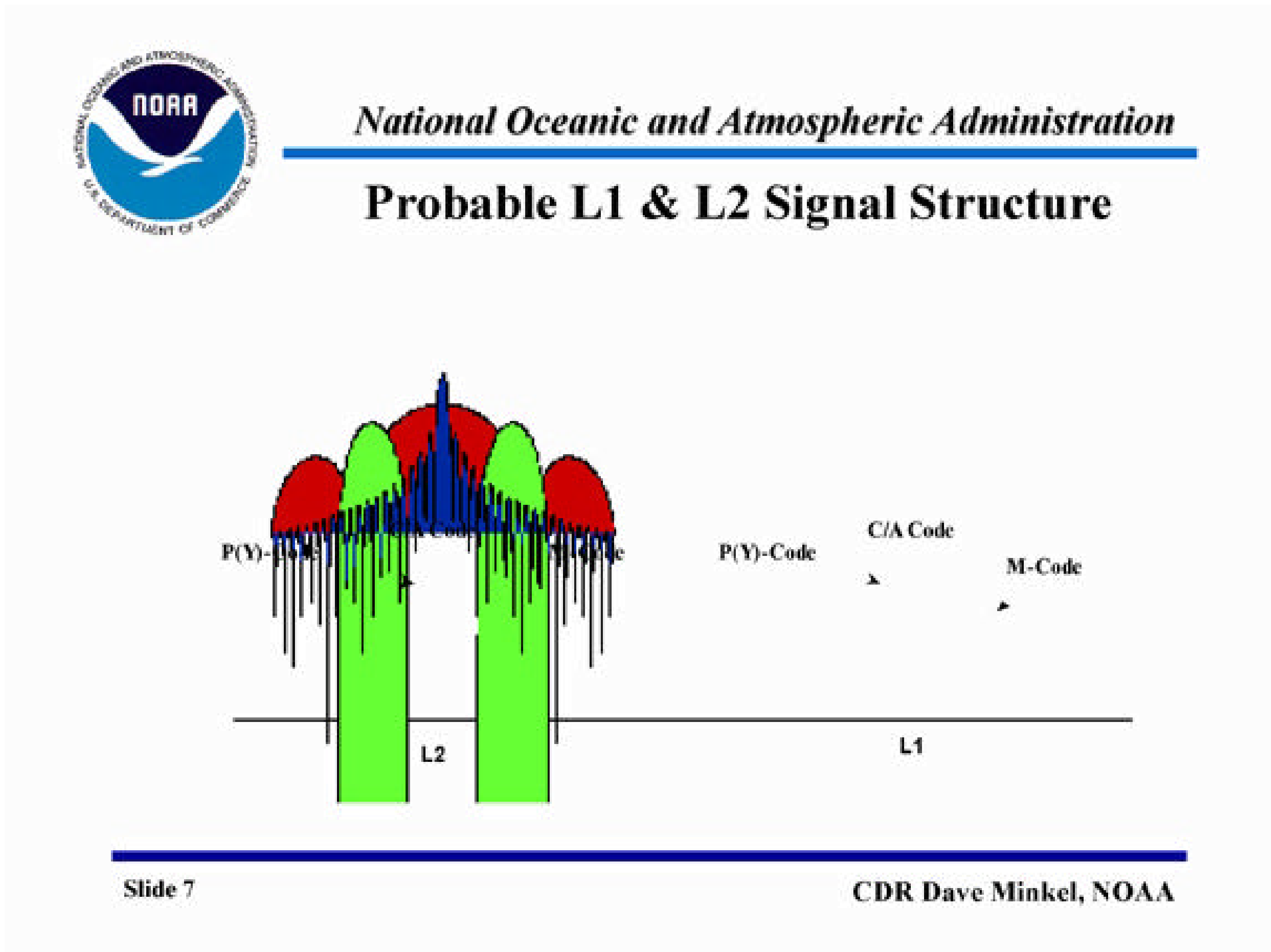
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Probable L1 & L2 Signal Structure
P(Y)-Code
C/A Code
M-Code
L2
L1
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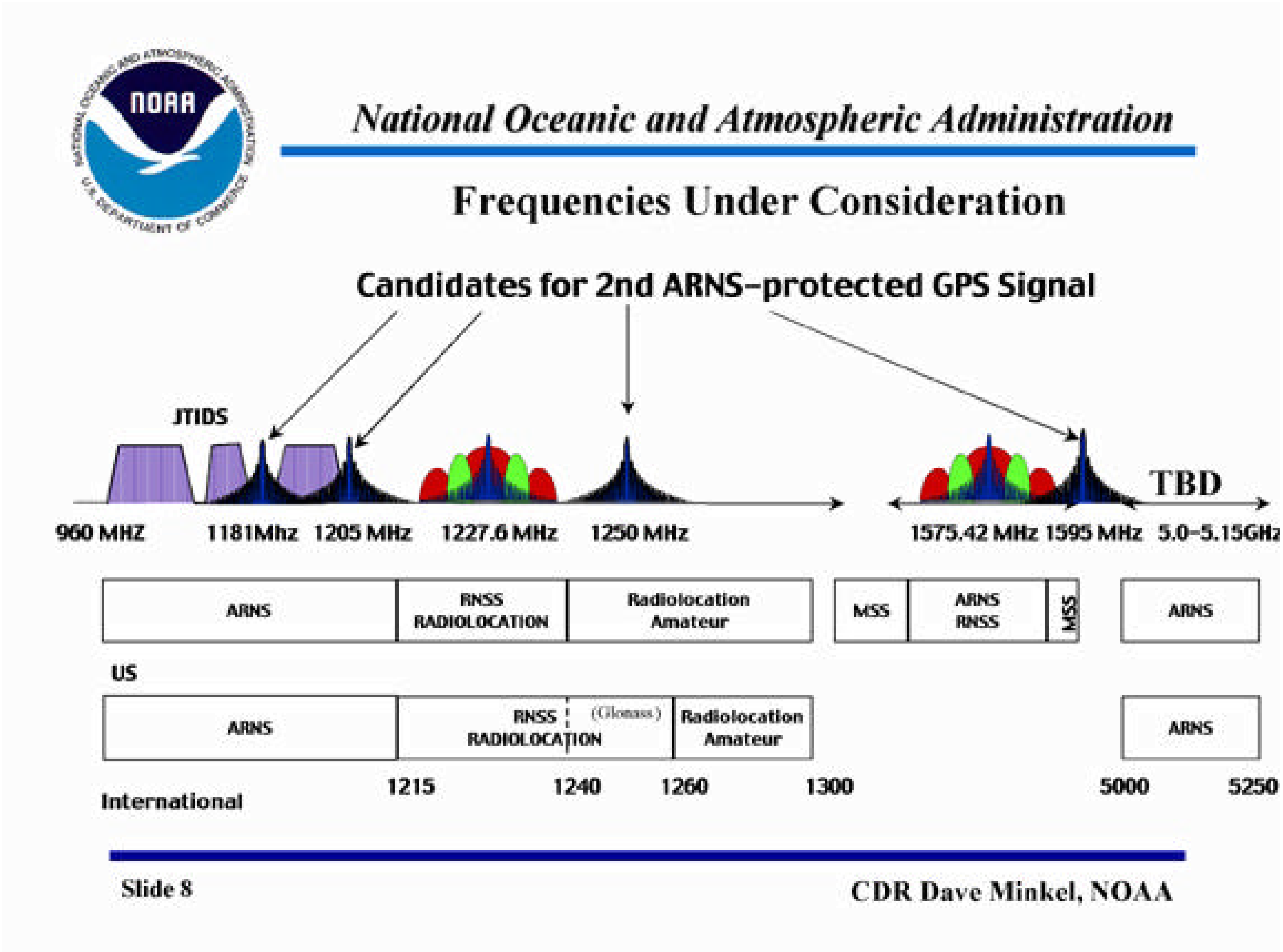

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Frequencies Under Consideration
Candidates for 2nd ARNS-protected GPS Signal
JTIDS
TBD
960 MHZ
1181Mhz
1205 MHz
1227.6 MHz
1250 MHz
1575.42 MHz
1595 MHz
5.0-5.15GHz
ARNS
RNSS RADIOLOCATION
Radiolocation Amateur
MSS
ARNS RNSS
MSS
ARNS
US
ARNS
RNSS RADIOLOCATION
(Glonass)
Radiolocation Amateur
ARNS
International
1215
1240
1260
1300
5000
5250
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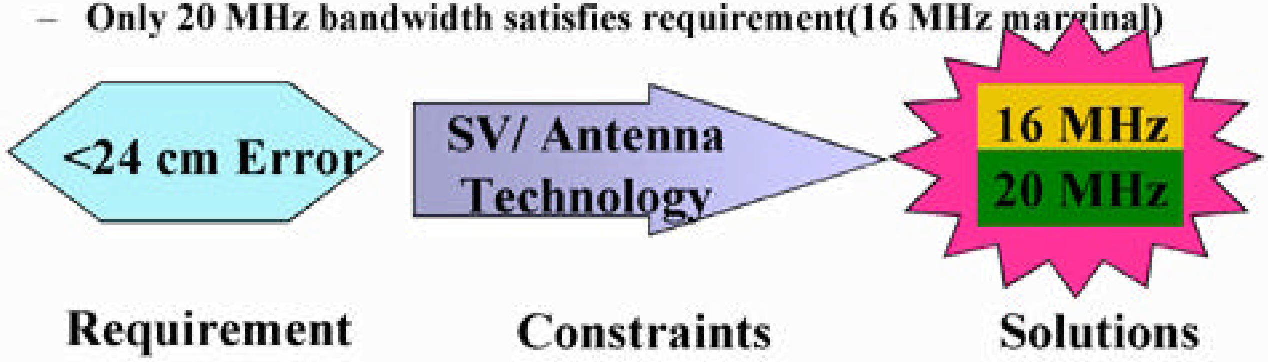
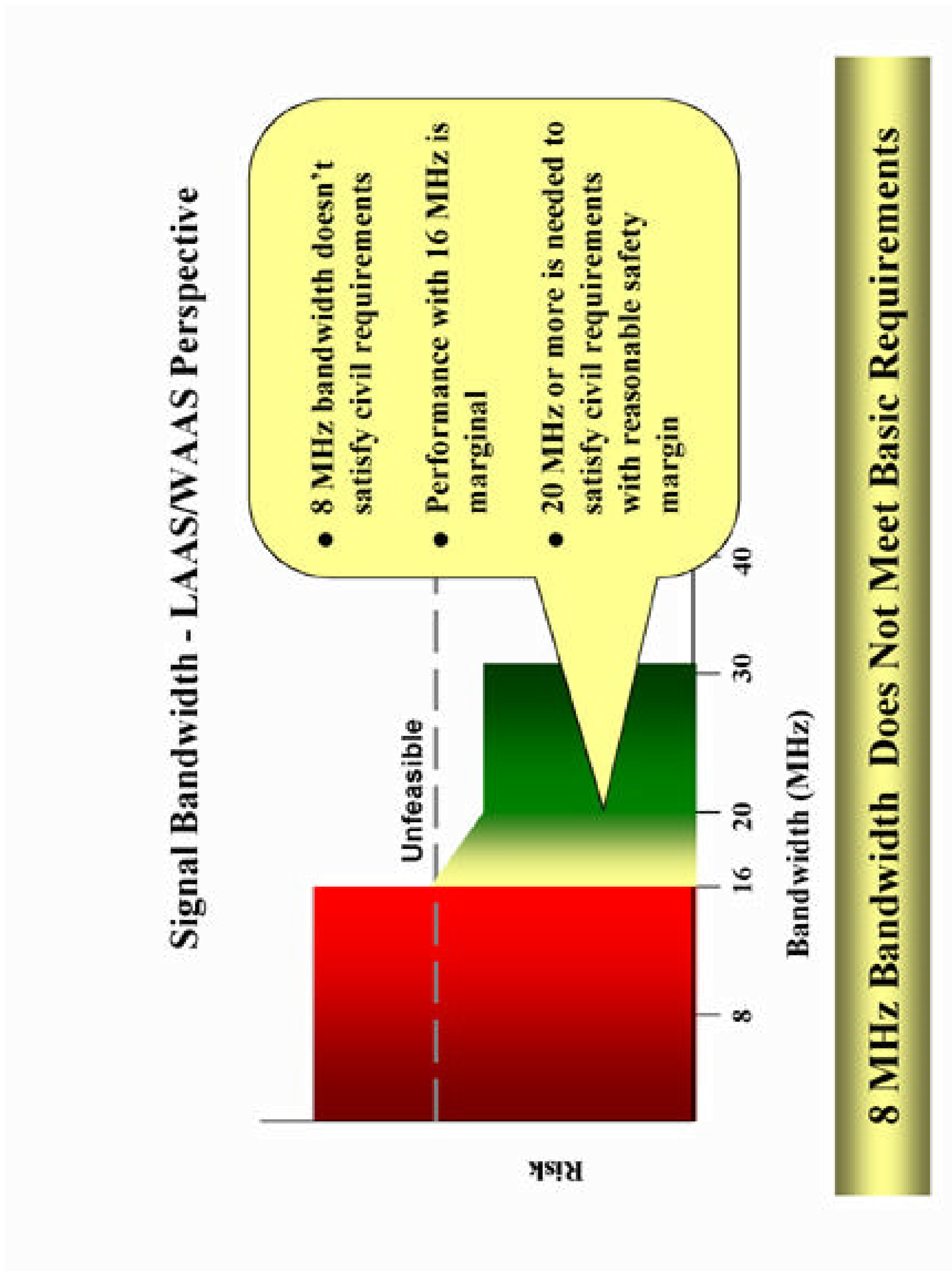
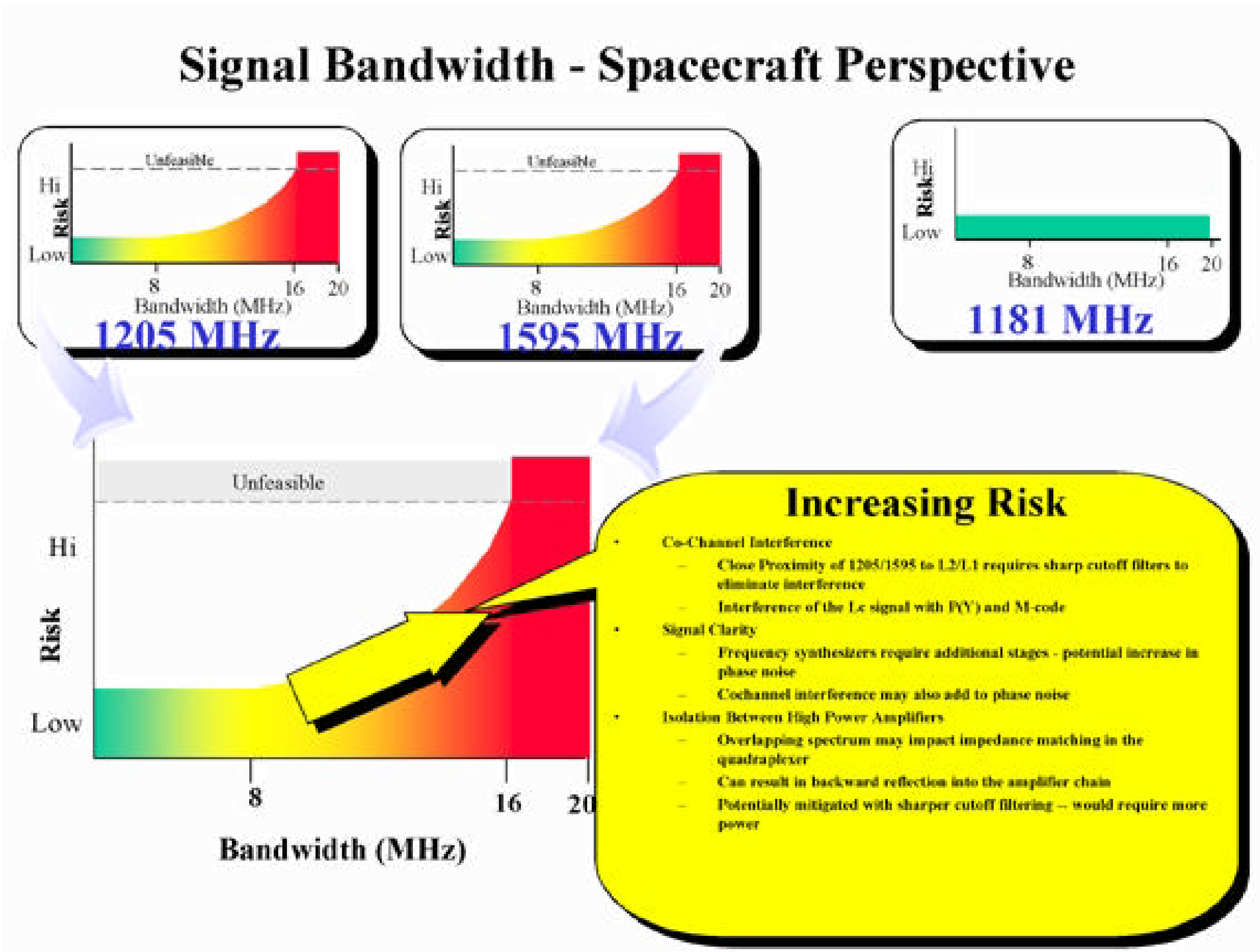
Bandwidth Analysis Approach

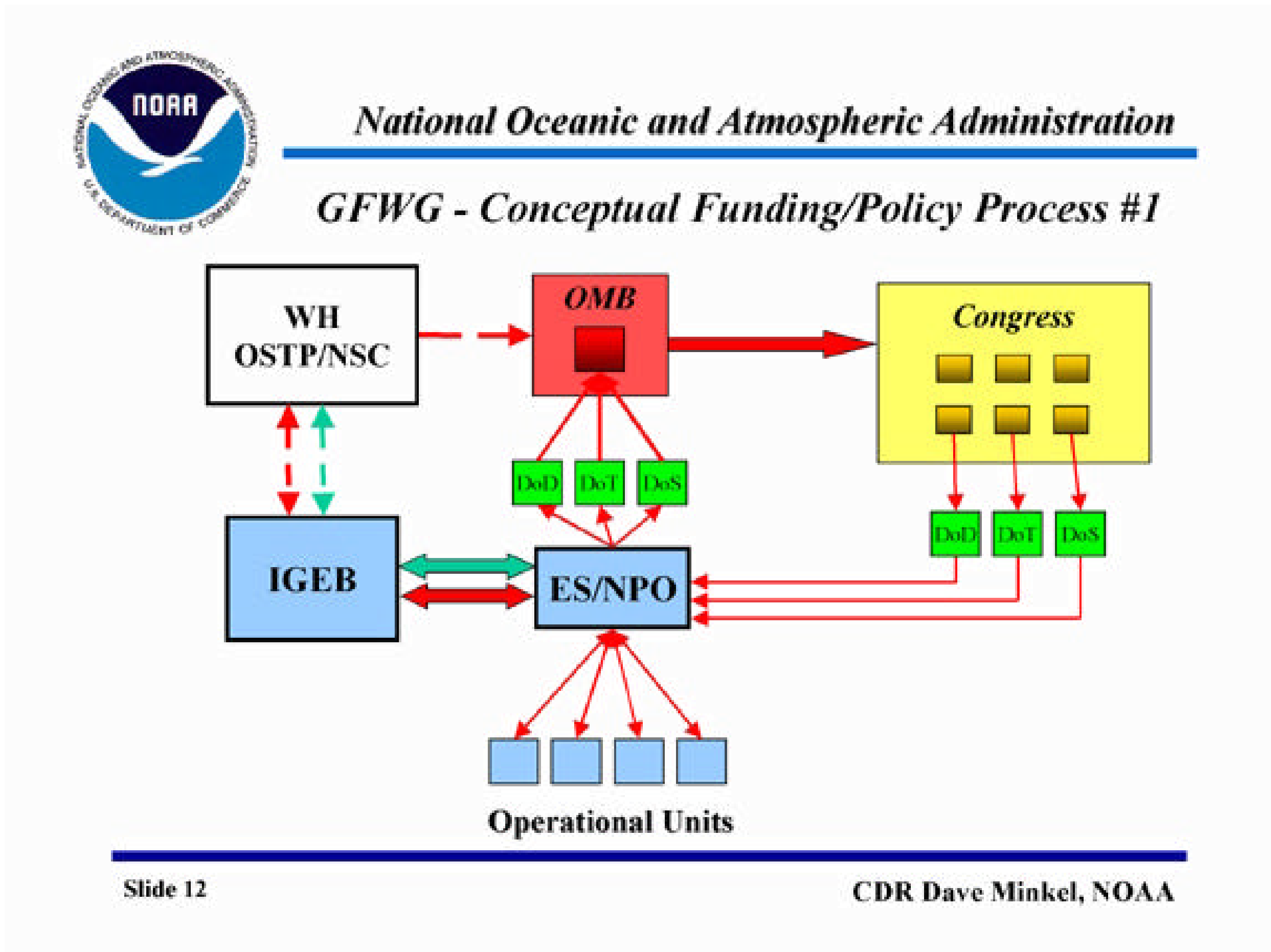
- Identify most stringent performance requirements
  - LAAS/WAAS requirement of less than 24 cm psuedorange error
  - Error budget includes all possible geometries and best available antenna attenuation techniques
- Evaluate alternatives
  - Analyses included 8 MHz bandwidth signals with both a higher chipping rate and longer correlation length codes
  - 16 and 20 MHz bandwidth signals also analyzed
- Select bandwidth driven solution
  - Only 20 MHz bandwidth satisfies requirement(16 MHz marginal)





Signal Bandwidth - LAAS/WAAS Perspective
Risk
Unfeasible
8
16
20
30
40
Bandwidth (MHz)
• 8 MHz bandwidth doesn't satisfy civil requirements
• Performance with 16 MHz is marginal
• 20 MHz or more is needed to satisfy civil requirements with reasonable safety margin
8 MHz Bandwidth Does Not Meet Basic Requirements


Signal Bandwidth - Spacecraft Perspective
Unfeasible
Hi
Risk
Low
8
16
20
Bandwidth (MHz)
1205 MHz
1595 MHz
1181 MHz
Increasing Risk
• Co-Channel Interference
– Close Proximity of 1205/1595 to L2/L1 requires sharp cutoff filters to eliminate interference
– Interference of the Lc signal with P(Y) and M-code
• Signal Clarity
– Frequency synthesizers require additional stages - potential increase in phase noise
– Cochannel interference may also add to phase noise
• Isolation Between High Power Amplifiers
– Overlapping spectrum may impact impedance matching in the quadraplexer
– Can result in backward reflection into the amplifier chain
– Potentially mitigated with sharper cutoff filtering -- would require more power


National Oceanic and Atmospheric Administration
GFWG - Conceptual Funding/Policy Process #1
WH
OSTP/NSC
OMB
Congress
DoD
DoT
DoS
DoD
DoT
DoS
IGEB
ES/NPO
Operational Units
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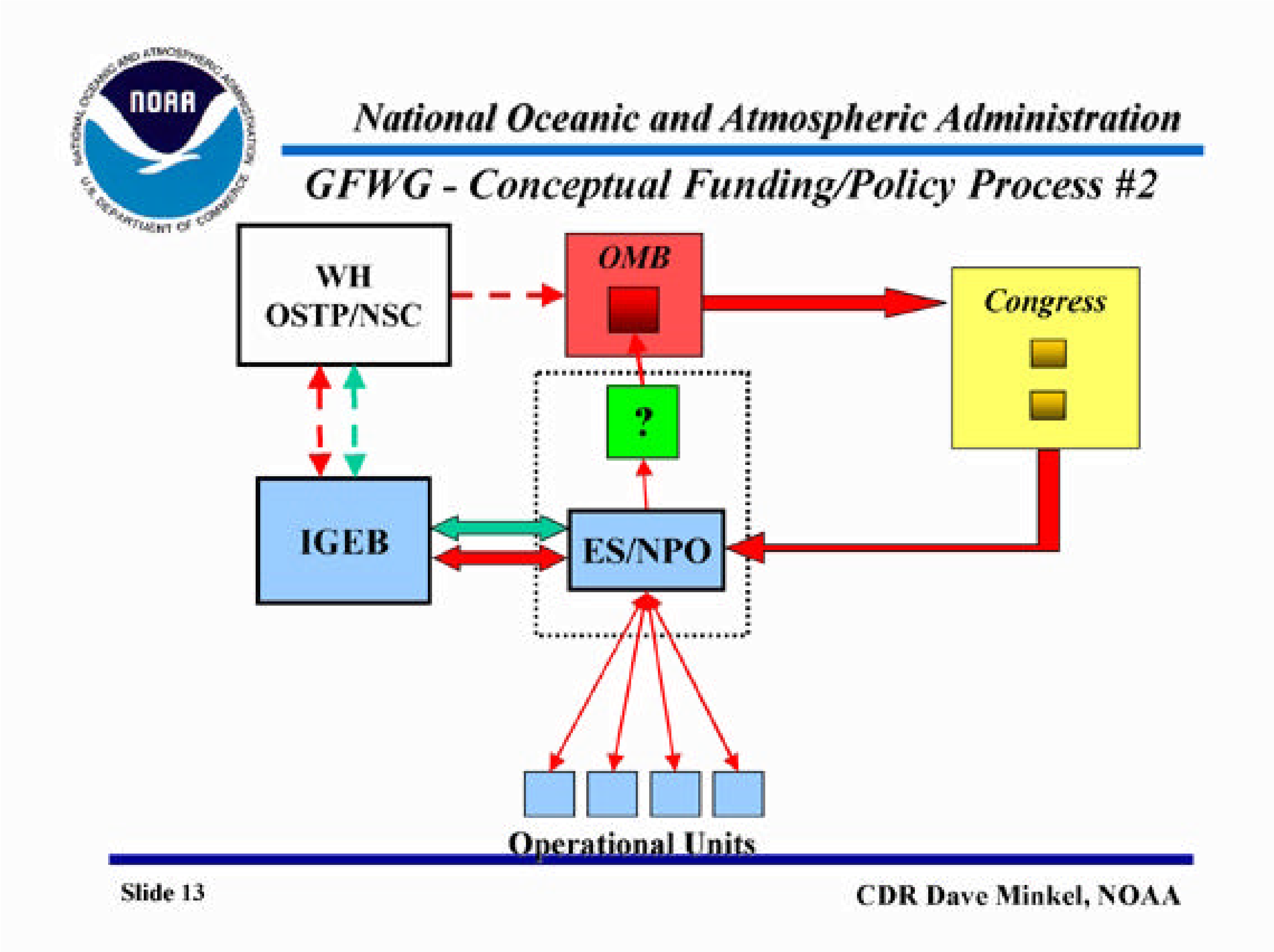
National Oceanic and Atmospheric Administration
GFWG - Conceptual Funding/Policy Process #2
WH
OSTP/NSC
OMB
Congress
?
IGEB
ES/NPO
Operational Units
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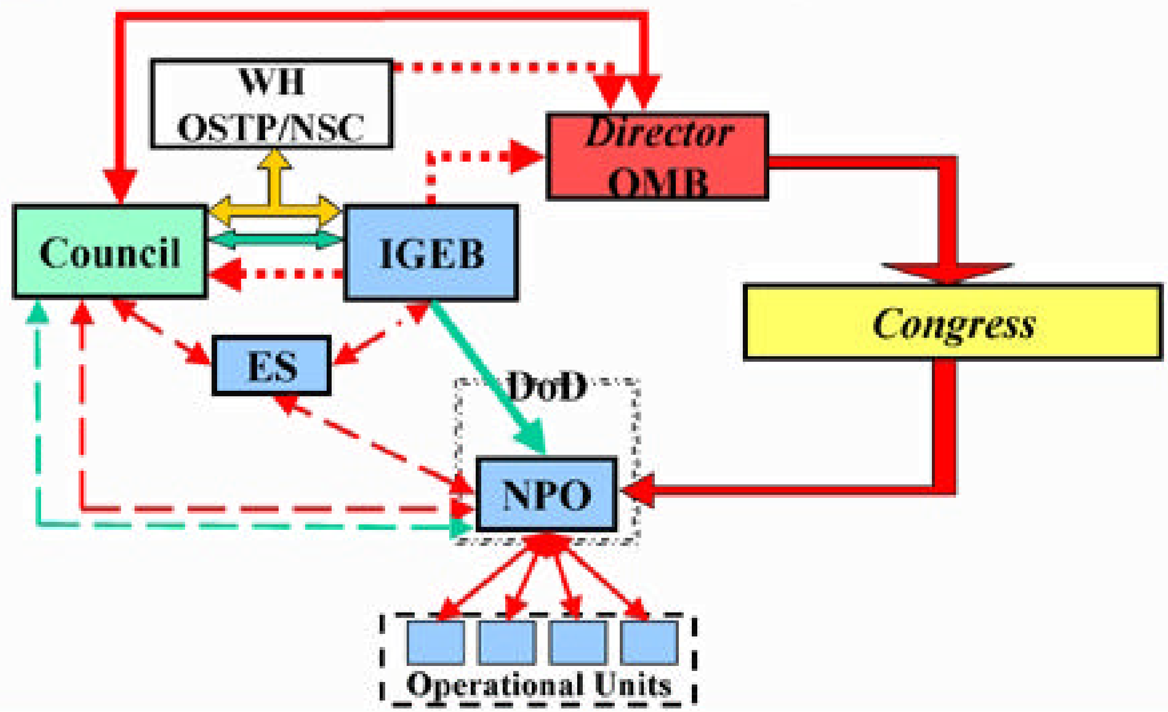
GMWG - Conceptual Funding/Policy Process #3



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GPS Interagency Advisory Council

- Represents the Non-transportation users of GPS
- Formed by MoA between Secretaries of Interior and Transportation
- Chaired by Director, National Geodetic Survey

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dminkel@ngs.noaa.gov

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Important Aspects for Ionospheric Applications in Future IGS Network Performance

IGS Presentation, IGS Network Systems Workshop
NASA GSFC/CDDIS, Annapolis, MD, U.S.A., November 2-5, 1998

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- On Behalf of the IGS Ionosphere Working Group -

Introduction

The IGS Ionosphere Working Group was formally established on 28 May 1998. Since June, several Analysis Centers started to contribute with own ionosphere products to that new service; the number of Analysis Centers has grown to five in the meantime. The existing IGS network system is used, basically in two directions: 1) access to tracking data from the whole IGS ground stations network, 2) delivery and exchange of ionosphere products through the CDDIS IGS Global Data Center. Currently there is a delay of several days, until observation data from enough IGS ground stations has been accumulated at CDDIS, that there is a coverage of data around the globe sufficient for reliable ionosphere modeling.

The ionosphere is a rapidly changing medium. This becomes more and more evident as we approach the next solar maximum. Beyond its global feature, the ionosphere often shows structures and disturbances only being spread over regional or local areas - especially during periods of higher solar activity. It is very difficult to predict the ionosphere's behavior and even impossible in most cases.

Short-Term Aspects

The most important SHORT-TERM goal of the IGS Ionosphere Working Group is (ref. R1): The routine provision of global ionospheric TEC maps plus spacecraft differential code biases (DCBs) with a delay of some days. To be able to fulfill this task, the following services must be provided by the IGS network system to the IGS Ionosphere Working Group:

- Globally well distributed and dense network of ground stations. Coverage gaps for ionospherically interesting areas that are not currently well observed should be filled: polar regions, southern oceans, Siberia & Asia, and the equatorial region. In particular, to specify the ionosphere in the equatorial region properly more sites are needed. The ideal would be three bands of sites at +15, 0, -15 degrees latitude with a site every 10-15 degrees in longitude.

- Fast availability of tracking data to enable the working group to provide products which really represent the ionosphere's actual state, thus accounting for its rapid changes. The delivery of hourly RINEX files to CDDIS from some of the IGS stations is a first good step into that direction.

Medium- and Long-Term Aspects

Regarding MEDIUM- and LONG-TERM goals of the working group, more sophisticated ionosphere models, provision of regional and local models, and near-real-time and real-time applications will become important tasks. For this, the IGS Ionosphere Working Group needs the following services from the IGS Network System:

- Extension of the fast tracking data delivery, which has just been started by the IGS for some stations into two directions:
  1. Extend the number of IGS stations which collect tracking data hourly.
  2. Increase the data retrieval rate to near-real-time or real-time capability from as many IGS sites as possible, ideally for the entire IGS network.

- Inclusion of GLONASS tracking data (IGEX) beyond GPS might improve the sky coverage.

- The current sampling rate of 30-second is sufficient for most ionospheric mapping applications. However, with regard to anticipated more sophisticated modeling, effects become significant which cannot be observed with 30-second pseudorange and phase observables, since they give very little visibility into ionospheric irregularities and their effects (signal fading, phase fluctuations). To really allow for observing effects of that kind, 1-second sampling rates would be of great benefit (at least upon the working group's request for certain IGS stations over selected time periods). Deep signal fades and phase fluctuations are of increasing interest in the GPS and ionosphere community due to increased reliance on GPS-based navigation and WADGPS systems, where continuous availability and high accuracy are of great importance.

- Concerning the deployment of new receivers at the IGS tracking sites, an ideal ionosphere monitoring receiver would use the 50 Hz sampling inside the tracking loop to compute ionospheric scintillation indices. A global network of such receivers would allow the monitoring of scintillation in real-time, accumulate a database of ionosphere irregularity information through the coming solar maximum, and provide a baseline for scintillation forecasting models. Such knowledge of scintillation is essential to guarantee stable performance of WADGPS systems.

- To get accurate slant TEC measurements a good knowledge of satellite and receiver differential code biases is very important. While estimates of the GPS satellite differential code biases indicate that these seem to be quite stable, estimated receiver biases clearly show higher day-to-day variability and larger formal errors. Diurnal variations in receiver biases, presumably due to temperature variations which affect the hardware, have been observed. Such variations can be expected to be quite large for some exposed field sites, and might be averaged out in ionosphere model fits. This problem could be overcome in a new receiver generation by an improved design ensuring the L1-L2 bias to be stable under field operating conditions. New receiver antenna systems with narrower filters are designed to screen out radio-frequency interference (RFI). Unfortunately, these narrower filters might introduce an additional L1/L2 bias that will be temperature dependent, introducing an additional instability from the ionospheric analyst's point of view.

References

R1: Feltens, J. and S. Schaer (1998): 'IGS Products for the Ionosphere.', IGS Position Paper, Proceedings of the IGS Analysis Centers Workshop, Darmstadt, Germany, February 9-11, 1998, pp 225-232. This paper can also be accessed in

PDF format: <http://gauss.gge.unb.ca/IGS/final/ionopp98.pdf>,

Postscript file: FTP anonymous@ubeclu.unibe.ch,/aiub$ftp/papers/ionopp98.ps

Acknowledgements

Special thanks are expressed to Mr. Brian Wilson (Ionosphere Group at JPL) for his valuable input into the above summary.

Some Remarks on New and Existing Tropospheric Products

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(2) Hawaii Institute of Geophysics and Planetology, 2525 Correa Road, Honolulu, Hawaii 96822, USA; e-mail: bevis@soest.hawaii.edu

The IGS has produced a tropospheric product on a regular basis since the beginning of 1997.This product is a weighted least squares estimate for the zenith neutral delay (ZND) at selected IGS stations. The number of sites involved has steadily grown and is now about 150. Estimates for more than 80 sites are provided by 3 or more Analysis Centers (see Figure 1). For these sites reasonable estimates of internal consistency can be obtained.

The quality for the majority of sites is good (±4 to 6 mm ZND), but at a few sites significantly larger biases and/or scatter are observed (see Figure 2). For the existing IGS Tropospheric Product no special demands on data latency exist. It is a post -processed product which is generated during or after the computation of the Final IGS Products (orbits etc.). In this non-real time context the outstanding problem is the lack of existing surface meteorological data at most IGS stations. Despite the fact that IGS has encouraged its members to add suitable met packages to the IGS tracking stations, very little progress has been made during the last two years. At the moment only 30 sites are equipped with met packages:

ALBH	ALGO	AOML	AUCK	BAHR	BRUS	CHAT	FAIR	GODE	HERS
INEG	KIT3	KOKB	LHAS	MDO1	METS	NRC1	OBER	PENC	POTS
PRDS	REYK	SOL1	STJO	USNO	WES2	WTZR	YELL	ZIMM	ZWEN

Unfortunately, for some sites data quality is not good enough. The precision of the sensors is not usually the problem, however. Rather, there are too many meteorological data gaps (often days long), and in such cases no meaningful series of water vapor may be compiled. Such sites are e.g. FAIR, GODE, KOKB, YELL, where data are only collected during VLBI experiments. To support the decision as to where future met packages should be installed, IGS will maintain a list of high priority candidate sites. Criterions for the selection may be the quality of the tropospheric estimates (see Figure 2) and the location of the sites (e.g. equatorial regions may be especially interesting).

Another problem associated with the present post-processed regime is that only 'on-line' stations (data delivery within 48 hours) contributing to orbit production are included in the IGS troposphere product. Stations reporting weeks late are not used, even if they are associated with surface meteorological measurements.

The number of projects and activities involving nearly real-time (NRT) monitoring of water vapor using ground-based GPS is steadily increasing. In all recommendations it is stated that IGS itself will not contribute to real-time water vapor estimation and therefore will not be directly involved in operational weather forecasting. However, IGS can support all regional activities of this kind by generating predicted orbits or, better still, near real-time (NRT) orbits based on hourly downloads of a subset of the global tracking network. At present this NRT subset of the IGS net is dominated by NASA stations. But it is anticipated that other groups associated with IGS will soon be contributing hourly RINEX files from stations that are easily connected to internet.

The predicted orbits already produced by IGS can be used for all real-time activities. The quality of the product may be improved in future. It is widely recognized, however, that a NRT orbit produced on a continuous basis by assimilating all available hourly RINEX files will be more reliable than any predicted orbit based on daily RINEX files.

The hourly RINEX data will be useful for regional analysis centers as well as for NRT orbit production. Many regional real-time activities would benefit from additional data from local IGS stations or from adjacent areas, and could use it to strengthen their regional solutions. For example including more long baselines into a regional analysis tends to stiffen estimates of the absolute (versus relative) values of the ZND and precipitable water (PW) at each station.

In the regional context it may be necessary to download data more than once per hour. For example, the NOAA GPS PW network in the USA already downloads its stations every 30 minutes. Total latency associated with accessing the data and analyzing it is another concern. It may be best for the analyzing groups to get the hourly IGS files directly from the operational data centers. If this can be realized than it would be nice if the archive structure in the data centers could be standardized (ideally one, possible also a very few variants). What about the hourly met-sensor-data? This is not important at present. Only the NRT-RINEX data of IGS are needed to support the regional activities. However, if we decide in future to have them also in NRT then the met data should be included with the RINEX data (special comments in the RINEX data; proposal from UNAVCO 1995). In this way the number of files to be handled by FTP will not grow unduly.

For some applications a total delay of 2 hours is the most that can be accepted. If in this case hourly data batches are not appropriate than a switch to 30-minute batches should be foreseen. In principle this would present no problem. However, it would demand a new naming convention since there are less than 48 letters in the alphabet. IGS should go ahead and define a new naming convention capable of supporting at least 48 sessions per day before we need to use it. This can be part of a more general consideration of naming conventions.

Although IGS will never be involved in NRT regional PW analysis, since this is a task more suited to individual countries or regional organizations, it may wish eventually contribute to this effort by estimating NRT PW at a small number of IGS stations that contribute to NRT orbit production, and have suitable met packages. If these NRT PW solutions were made available along with the NRT orbits, they could be routinely compared to the NRT PW solutions produced by regional groups as a quality control mechanism. If the IGS and regional PW solutions suddenly diverged in a pronounced fashion, then this would flag a problem in either the IGS or the regional analysis. Given the importance and difficulty of quality control in NRT settings, this intercomparison would be very useful.

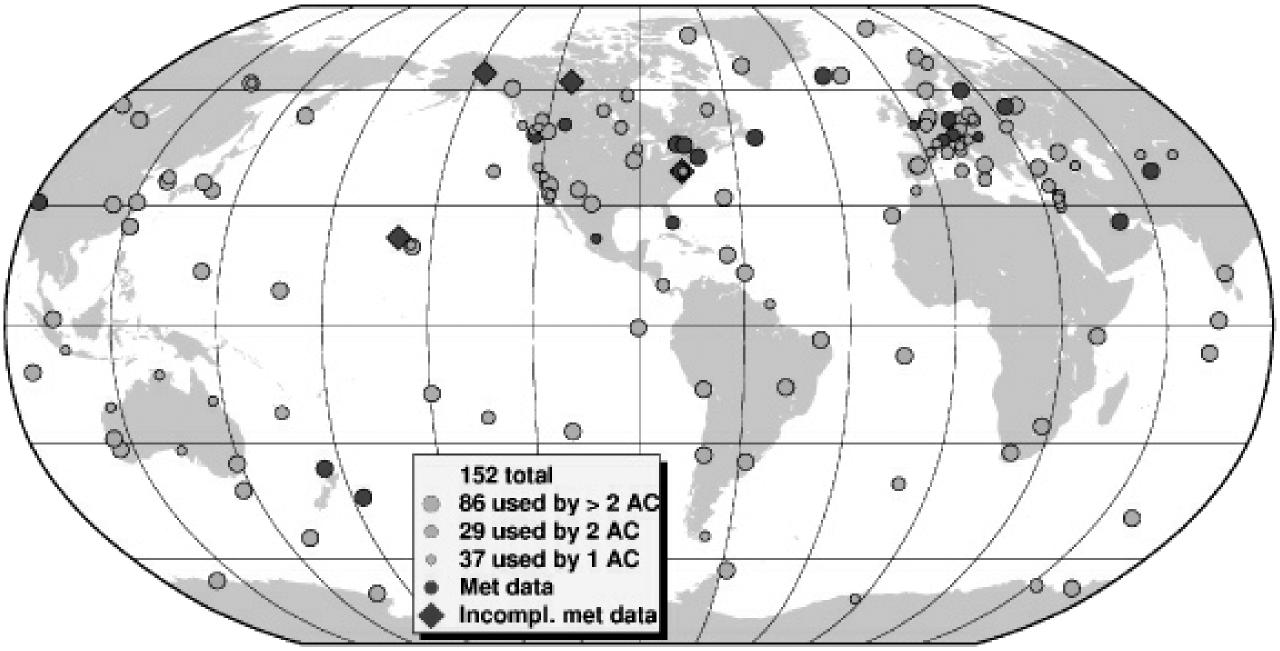

Fig. 1: IGS stations with tropospheric estimates. The existing meteorological packages are given.

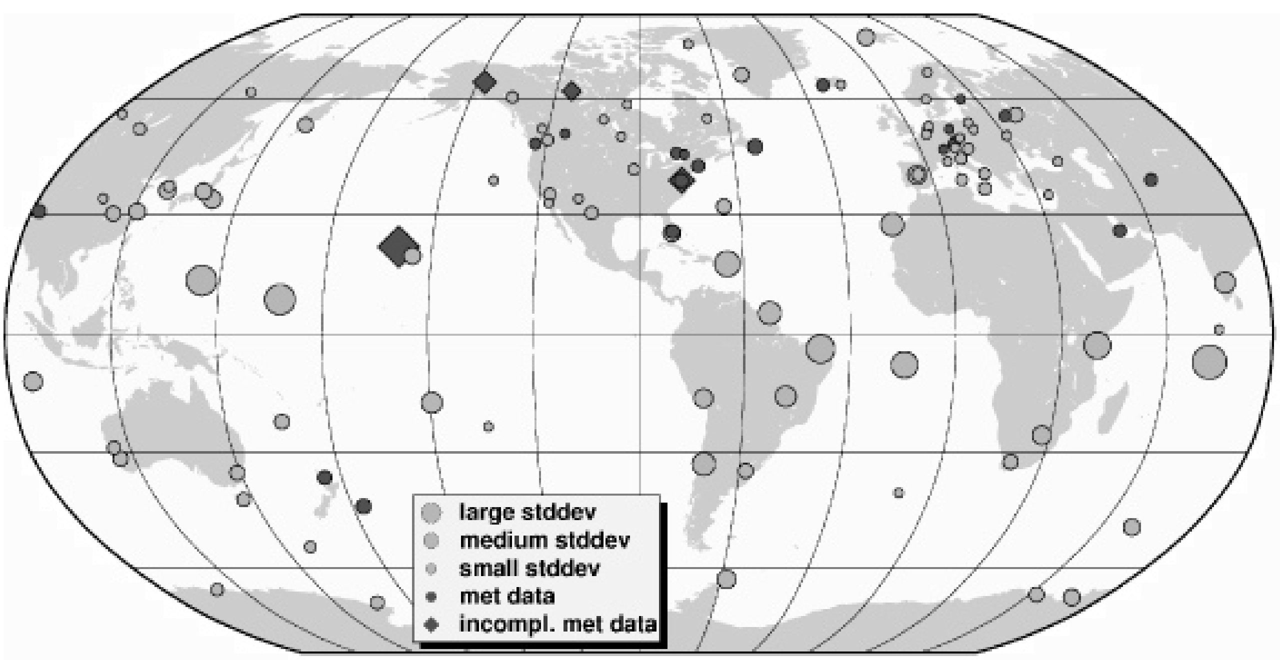

Fig. 2: IGS stations with tropospheric estimates. The quality of estimates is indicated and the existing met sensors are marked.

IGS Data From a Tectonic User's Perspective

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33 40 Mitchell Lane, Boulder, Colorado 80301

From the perspective of geologists interested in studying tectonic processes, IGS data are important for several purposes. All reflect the data's being publicly available, continuous, long time series of high quality.

First, IGS data provide much of the best data for global plate motions on 10-year time, to compare with 3-Myr geological models such as NUVEL-1. In general, the results are surprisingly similar, indicating uniformity of plate motions, presumably due to the viscous asthenosphere damping out episodic (earthquake) motion at plate boundaries. IGS data are also crucial to resolve plate motions in cases where the 3-Myr model is poor due to plate geometry (e.g. Caribbean, Nubia-Somalia / East African Rift).

Second, IGS sites provide much of the best data to measure rigidity of plate interiors and hence constrain intraplate deformation and the causes of intraplate earthquakes. For example, eastern North America turns out to be rigid to better than 2 mm/yr. This observation implies the recurrence time for great New Madrid earthquakes, such as occurred in 1811-1812, is much longer than previously thought, so their seismic hazard is much less than previously assumed.

Third, IGS data provide crucial products (ITRF, orbits, etc) to support high precision local surveys of plate boundary zones, making it possible to map the deformation field within these zones and tie it to global plate motions. Exciting results from such zones around the world (e.g. Andes, Western North America, Mediterranean, Tien Shan, Himalaya, etc.) are being used to better understand the mechanics of such zones and the associated geologic hazards.

Hence, from a tectonic user's perspective, the GPS technology and data analysis are mature, although improvements are still coming. Thus the GPS data are an intermediate quantity needed for the geologically important results: site motion vectors. The vectors are usable without knowledge of GPS (by analogy to earthquake moment tensors or plate motion rates from magnetic anomalies), and so can be widely used in the geological community. It is becoming standard to form motion vectors by combining various GPS (as well as SLR, VLBI, and DORIS) data. These vectors are then integrated with other data types (seismological, geological, etc.) to investigate tectonic processes

Given these developments, tectonic users hope to see IGS continue and expand its current approach. They need publicly available long, stable, time series for high precision data. They would like to see the global site distribution improved, including more sites in Africa and South America. Finally, so that improved motion vectors can be estimated, it is crucial that these data be archived for the long term.

IGS/BIPM Time Transfer Project

Jim Ray

U.S. Naval Observatory
Washington, DC, USA

The IGS has joined with the Bureau International des Poids et Mesures (BIPM) in a pilot project to study accurate time and frequency transfer using GPS carrier phase and pseudorange observations. About 35 groups responded to the Call for Participation to form a working group, co-chaired by G. Petit (BIPM) and J. Ray (U.S. Naval Observatory). The project was formally initiated on 18 March 1998. Detailed information on the project and its activities is available at the Web site http://maia.usno.navy.mil/gpst.html.

A number of groups have been working for several years to develop the capability of using geodetic GPS techniques for accurate time and frequency transfer. A variety of convincing demonstrations has already been performed showing the potential for determining clock differences at the level of a few hundred picoseconds (ps). The current state of maturity of both the global tracking network and data analysis techniques now allow practical applications to be considered. The central goal of this Pilot Project is to investigate and develop operational strategies to exploit GPS measurements for improved availability of accurate time and frequency comparisons worldwide. This will become especially significant for maintaining the international UTC timescale as a new generation of improved frequency standards emerges.

For most geodetic applications, receiver and satellite clocks can be treated as true nuisance effects. Any GPS signal delay common to all observations at a given epoch, whether due to a genuine clock-related timing variation or to some other non-clock bias, will be interpreted in the data analysis as a clock-like effect. But, by the same token, because such effects are common to all simultaneous observations and are nuisances, they can be removed altogether by forming observation differences (usually, double differences between pairs of receivers to a single satellite to eliminate satellite clocks and between pairs of satellites involving a single receiver to eliminate receiver clocks). With undifferenced data, combining pseudorange and carrier phase observations allows the clock-like effects (including the true clock as well as other similar biases) to be determined directly. However, only differential clock variations can be estimated. That is, a single receiver clock is normally chosen as a reference and all others are determined relative to that reference.

The behavior of the clocks (both satellite and receiver) has intrinsic interest and usefulness for applications other than global time and frequency transfer. Even for certain geodetic applications, retaining the clock information is useful. This is particularly true for exploiting the computationally efficient method of "precise point positioning" [Zumberge et al., 1997] which uses externally supplied precise orbit and satellite clock information to estimate the position and clock values for an isolated receiver. The IGS combined ephemerides and satellite clock products (distributed in sp3-format files), for example, can be used in this way. Another interest is for monitoring the operational performance and health of a receiver's frequency standard.

Within the timekeeping community, there is considerable interest in the potential of using GPS carrier phase data to improve time and frequency comparisons globally. Current techniques allow long-distance comparisons no better than a few nanoseconds (ns), whereas the precision of the geodetic carrier phase method is about 10 times better. The main emphasis of the IGS/BIPM pilot project is to address the issues associated with such applications. Naturally, therefore, IGS receivers located at timing laboratories are critically important. Precise and accurate time comparisons between them could enable improved maintenance of the TAI international atomic timescale. They also offer the potential for the IGS to relate its derived clock products to UTC/TAI rather than the GPS broadcast timescale. In addition, the considerable number of IGS receivers equipped with very stable frequency standards (particularly H-masers and cesium clocks), but not located at timing labs, could possibly augment the TAI ensemble.

The initial efforts of the IGS/BIPM project are directed to: 1) deploy additional GPS receivers at timing labs and upgrade existing stations for improved performance and stability; 2) develop strategies for GPS data analysis of a large number of estimated clocks and implement these within the IGS products; 3) analyze the delays within GPS equipment and related hardware and develop techniques for calibrating the time offset compared with external standards; and 4) conduct comparisons with independent, simultaneous techniques.

Frequency Standards

For time and frequency applications, a frequency standard of the highest stability is preferred. Generally, the available commercial options, in order of decreasing preference, are: 1) active cavity-tuned H-masers (e.g., Sigma Tau), which maintain a selected frequency state relatively stably for long periods; 2) passive H-masers, which continuously drift in frequency; 3) high-performance cesiums (e.g., HP 5071A); 4) other cesiums; 5) rubidiums; 6) high-performance crystals; 7) other crystals (e.g., internal receiver oscillator). VLBI stations are invariably equipped with H-masers so colocated IGS stations are strongly encouraged to arrange to use the same standards (which most do). This has the added benefit of allowing comparisons between GPS- and VLBI-derived clock estimates.

Within the current IGS network of roughly 200 stations, about 30 are equipped with H-maser frequency standards, about 20 with cesium clocks, and about 20 with rubidium clocks. The remainder use internal crystal oscillators. About 12 IGS stations are located at timing laboratories, although this number is expected to grow. Of these, only a handful are colocated with two-way satellite time transfer facilities (all in Europe or North America), which is the technique generally regarded as the current state-of-the-art.

All frequency standards are sensitive to changes in their environment. Thus, isolated, controlled chambers are generally preferred to house them, especially the most stable types. On the other hand, the signal input cables to the receiver (for 5 MHz, 20 MHz, 1 pps, etc.) can degrade the performance, especially if the cable runs are long. Every effort should be made to minimize the cable runs, use cable types with low temperature sensitivities (no worse than 1 ps/degree/m), and maintain stable environmental controls. It is expected that the IGS/BIPM project will produce recommendations for cable types and environmental specifications.

Receivers

Because the requirements for geodesy and timing have historically been viewed as quite different by manufacturers, the current choices are less than optimal. It is generally not possible to accurately relate the internal timekeeping of geodetic receivers (where observations are made and time-tagged) to an external standard, a limitation which clearly inhibits their usefulness for time transfer. Furthermore, some geodetic receivers (e.g., AOA TurboRogue) can spontaneously reset their internal clocks, sometimes annoyingly often. However, these shortcoming have been recognized and are being addressed. In the meantime, an overall receiver time bias, even one which occasionally changes discontinuously, does not restrict the usefulness of existing receivers to study frequency differences. Indeed, this has already been shown for some stations with strict "metrological" stability standards [for example, Larson et al., 1998].

Where feasible, the clock discontinuity caused by a spontaneous TurboRogue internal reset can be quantitatively calibrated by monitoring the receiver 1 pps output signal against the 5 MHz input. It has been shown that, with a very stable and accurate time interval measurement system, the 1 pps data can be used to calibrate receiver clock resets probably to the few ps level.

Studies of individual receivers for their time and frequency stability characteristics are limited so far, but there are reports of large and highly variable sensitivities to temperature changes. These can be of the order of 100 ps/degree. So, as with frequency standards, isolated controlled environments are strongly recommended.

Antennas and Cables

Because of its length and exposure to outside conditions (usually), the RF cable from the antenna to the receiver can be a leading source of varying instrumental delay, which is indistiguishable in the data analysis from the frequency variations due to the frequency standard itself. If the frequency standard is highly stable (e.g., H-masers), then the RF cable can set the overall frequency stability limit for a station. Common cable temperature sensitivities are about 1 ps/degree/m and cables are often 100 m or longer. At USNO we recently replaced a RG-217/U cable with phase stabilized Andrew FSJ1-50A and found a dramatic improvement in frequency stability. More stable cables are always more expensive and usually more difficult to work with so the value of such a change must be evaluated against the potential benefit and must take into account the stability performance of the local frequency standard.

The antennas themselves also possess some sensitivity to temperature changes (an effect which is frequency dependent) although these have not been well studied so far. Based on the observed behavior of the most stable IGS sites, the antenna related effects do not appear to be significant, at least not for antennas designed for observations of GPS only and over intervals of hours to days. Heated antenna units, which maintain a constant temperature, are available but there is insufficient experience and analysis to assess their general utility. (Such units may be necessary for the wider bandwidths needed for dual observations of GPS and GLONASS.)

Reports and Logs

For performance assessments and other analyses, it is highly desirable for IGS station operators to report all events -- planned or unplanned -- which might affect the frequency or timing behavior. In addition to the hardware changes that should be updated in the site logs, other events such as adjustments to the frequency setting should be noted in timely IGS Mail messages.

New types of information should be included in the IGS site logs, including particularly the cable types, lengths, and specifications for the RF cable from the antenna to the receiver, and the cable to the receiver from any external frequency standard. Additional detail for the current log information is encouraged, such as the model type for the frequency standard.

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International GLONASS Experiment (IGEX-98)

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Motivation

The Russian GLONASS system currently has 14 operational satellites. Combined with the 27 operational GPS satellites, this gives the user community access to 41 global navigation satellites. The GLONASS satellites are unencumbered with Selective Availability (SA) effects or anti-spoofing (AS) and a few manufacturers are producing receivers that can track both GLONASS and GPS satellites. GLONASS users can access dual-frequency P-code, enabling ionospheric corrections and more precision than the GPS C/A-code. The fact that each GLONASS satellite in view transmits on a unique pair of frequencies also makes the system less vulnerable as a whole to frequency interference. A number of factors, however, have made it difficult to use GLONASS including differences between the GLONASS and GPS reference frames and timing systems, a lack of high quality commercial receivers, some idiosyncracies in the broadcast information from the satellites, and the lack of precise orbits.

The navigation and scientific communities are very interested in GLONASS as an augmentation to GPS to improve integrity, reliability and accuracy through improved geometry and access to more satellites, especially in areas with limited visibility (mountains, canyons, city streets). As a result, several organizations -- the International Association of Geodesy, Commission VIII, International Coordination of Space Techniques, the International GPS Service (IGS), the Institute of Navigation (ION), and the International Earth Rotation Service -- are co-sponsoring the first global GLONASS observation campaign.

Objectives

The first objective of the campaign is to create a GLONASS data set with the following characteristics: globally-distributed, collocated with GPS stations, monumented and documented sites, adherence to common data standards, and collected over a long time period. In addition to producing this unique data set, the scientific objectives include:

- computation of precise orbits with accuracies of one meter or better in a well-defined Earth-fixed reference frame
- collection of satellite laser ranging (SLR) data for evaluation of the orbits computed directly from the GLONASS data
- evaluation of GLONASS receivers
- development and evaluation of software for orbit determination and applications
- evaluation of positioning capabilities with GLONASS alone and combined with GPS
- refined comparisons of the Russian PZ-90 reference frame with WGS 84 and ITRF
- refined comparisons of GLONASS and GPS time and time transfer applications
- stimulus for applications of the combined GLONASS and GPS data.

Tracking Campaign

The tracking campaign began on October 19, 1998 and will continue through January 22, 1999. Proposals were received for 87 stations in 34 countries. As of October 24, 33 stations were operational and sending data into the designated data centers. The Institut Géographique National in Paris and NASA's Goddard Space Flight Center in Greenbelt are acting as global data centers. Site logs, measurement data, broadcast orbits and clock information, and precise orbits are available from the global data centers.

Implications for the Future

IGEX-98 will provide insights into the concept of an augmented GPS constellation. Questions regarding reference frames, timing, tracking equipment, data standards, precise orbits and other system interoperability issues will have to be dealt with. The increased number of independent observations should provide more robustness and better spatial and temporal resolution for modeling and detection of events, especially for non-linear, rapdily changing or transient phenomena. How best to exploit this will be the challenge.

Network Implications for Global Change Monitoring

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Abstract

The complexity of the Earth system and our limited knowledge concerning the key indicators necessitate a more or less complete monitoring of the Earth system as well as adequate systems for delivery of information into decision-making. Global change impacts are mainly expected on decadal to inter-decadal time scales. Monitoring global change as a contribution to the developing environmental monitoring and assessment programmes therefore requires a crucial long-term component in the design of all aspects of networks. To assure the necessary long-term stability and consistency, a strong operational component is required. Due to a lack of a long-term mandate, services based on voluntary contributions may not be adequate to ensure this operational component. The often technique-oriented observing networks need to be developed along a global strategy and linked into issue-oriented information delivery systems.

Introduction

Over the last decade, a very rapid development of the space-geodetic observation techniques has led to unprecedented possibilities to measure positions and opened up for new geo-scientific applications (see Plag et al., 1998). Moreover, several space-geodetic methods including Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI) and the Global Positioning System (GPS) have reached a status where the transition from research to operational states appears to be feasible. These techniques have the potential to provide for a reliable long-term monitoring of key parameters describing the Earth's system, such as surface displacements and deformations, Earth orientation, integrated precipitable water vapour content of the atmosphere (IPWC), and electron density in the ionosphere. Moreover, they are the tools for the maintenance of a globally uniform reference system required for all position-dependent information.

Space-geodetic methods thus potentially can provide a valuable contribution to global or regional monitoring of global change. In fact, the IGS in its home page claims a "Monitoring of Global Change by Satellite Tracking". However, while such a claim is easily being formulated, it might not be so easy to actually provide a valuable contribution to Earth system monitoring for scientific and (even more so) societal applications. Due to the complexity of the Earth system, where all system processes are closely intertwined, a relevant contribution of IGS to the monitoring of global change can only be realised if this part of IGS's activities is integrated into a global context.

Environmental security is an issue of increasing importance for a society depending on ever expanding infrastructure and experiencing a concentration of a growing fraction of the population in megacities. Integrated with other techniques, the space-geodetic techniques could contribute to environmental monitoring, for example, with the important application of "early warning". Here, too, the value of this contribution will crucially depend on the ability of the space-geodetic community to link itself into a broader context.

Any service based upon an observing system may be viewed from three different aspects, which can be visualised as a triangle (Fig. 1). Each corner is of equal importance for the performance and success of the service. The triangle should be centred around the needs of the users of the service, which may be scientists or the society at large. The design of the *virtual network* including the objectives of the service needs to be such that the products correspond to scientific or societal need. Ideally, the design process should be user-driven, that is, the identification of the user's requirements should be the first step in developing the virtual network. The *physical realisation* of the network including the single stations, the communication tools, the data processing and the analysis has to meet the specifications resulting from the virtual network and, particularly, the objectives of the system. Quality-control of the performance of the physical network and the products as well as the long-term consistency of the operation need to be integral parts of the design of the virtual network. Finally, the *institutional network* has to ensure the political and financial support of the system. The institutional network has to identify the different actors and stakeholders all along the chain of information flow. This may range from research scientist over scientific organisation, governmental institutions and services, all the way to private enterprises. In particular, this includes the owners of the (physical) infrastructure as well as the "owners" of and contributors to the services provided by or linked to the virtual network. Most of all, the institutional network has to obtain the necessary long-term mandate from the users. In case of environmental monitoring, where both the users and the owners might be governmental bodies, a mandate from the relevant political level may be required to backup for long-term activities.

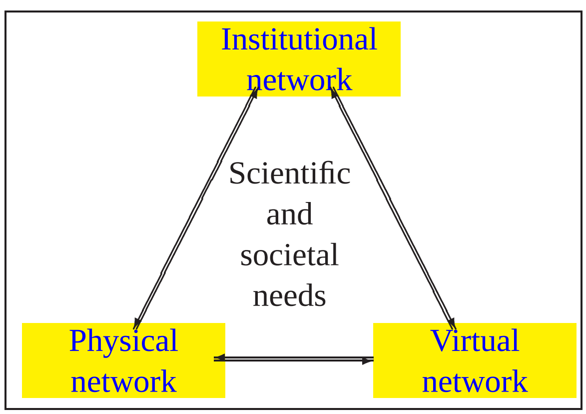

Figure 1: The Network Triangle.

An operational monitoring system should respond to well defined scientific and/or societal needs. The design of the virtual network should be user-driven. The physical network needs to comply to the specifications resulting from the virtual network. Within the institutional network, the owners of the physical and virtual network have to be linked with the users to provide for the necessary resources and the long-term mandate for the maintenance of the system. From Plag, 1999.

Below, some basic implications will be discussed, which follow for the virtual and institutional networks from IGS's quest for monitoring of global change. Prior to that, the general background in global Earth monitoring is very briefly described in the next section with main focus on the societal needs.

Developments in Global Monitoring

The need for a comprehensive monitoring and assessment of the global environment was formally acknowledged at the UN Conference on the Human Environment in Stockholm in 1972 with the adoption of an Action Plan. One of the three main components of this plan was the global environmental assessment programme (Earthwatch), which made a number of recommendations concerning evaluation and review, research, monitoring, and information exchange. In preparation of the UN Conference on Environment and Development (UNCED) in Rio in 1992, the United Nation Environmental Programme (UNEP) Governing Council recommended in 1991 that "*Earthwatch should identify global and regional environmental monitoring and assessment needs, co-ordinate and harmonise global, regional and national monitoring and assessment programmes to the extent required, prepare comprehensive assessment statements, inventories and analytical statements, give advanced warning of emerging environmental threats, advise on causal relationships of observed environmental changes, and suggest policy responses and management options where necessary*". At the UNCED, the Agenda 21 was accepted as a plan to progress towards a sustainable development. In Chapter 40, the Agenda emphasised the rapidly increasing need in decision-making for environmental information, and the UN system-wide Earthwatch received a new impetus as one major instrument to implement the Agenda 21. Moreover, the role of Earthwatch was further strengthened in the reviewing of the Agenda 21 through the UN General Assembly Special Session in June 1997 (for a detailed documentation, see the documents available at the Earthwatch home page http://www.unep.ch/earthw.html. If not mentioned otherwise, all documents related to the following discussion are also available on this web site.).

Under the framework of Earthwatch, a strong international development has taken place over recent years towards a strategy for and implementation of a global observing system including the necessary tools to provide relevant information to the users. Of relevance for the discussion here are the development of an Integrated Global Observation Strategy (IGOS) and the implementation of the three Global Observing Systems (G3OS), namely the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Global Terrestrial Observing System (GTOS). It is not possible to give here an overview of the current strategies guiding the development in global observing and monitoring. However, it is worthwhile to highlight a few points.

In its newly available draft of "Earthwatch strategic framework for environmental observing, assessment and reporting", the main objectives of Earthwatch are described as

- "*to keep policy-makers informed of the global environmental situation, particularly where it threatens human health and well-being and environmental sustainability*";
- "*to provide adequate scientific information on the global environment assembled, integrated and organized so that the current status and trends can be summarized for each global report*";
- "*to provide the basis for integrated assessments of the global environment*".

While data collection is considered to be organised best by environmental components or location or by technologies or methods, it is supposed that delivery of information products will most often need to focus on specific issues. The draft identifies as one major gap in the flow and transformation of data into information in many case not the observation techniques but our ability and a lack of infrastructure to make use of the data. The economic strategy is considered to be as important as the information structure. No reason is seen why the essential environmental information necessary for environmental security is not publicly funded in the same way as many tasks relevant for the physical security of the society are.

In the draft document of IGOS it is stated that "*IGOS focuses specifically on the observing dimension of the process of providing environmental information for decision-making*", however, pointing out that data collection is not an end in itself. Among others, IGOS covers all forms of data collection concerning the physical, chemical and biological environments of the planet. IGOS attempts to unite "*the major satellite and ground based systems for global environmental observations for the atmosphere, the ocean and the land in a framework that delivers maximum benefit and effectiveness in their final use*". Building on existing national and international mechanisms, IGOS attempts to add values to these.

Among the five major components of considerable strategic importance to IGOS mentioned in the draft, the following three are mentioned here:

- Transition from research to operational: most environmental observations have been and still are collected by scientists as part of scientific programmes serving specific research questions. Funding, planning, and individual careers are not adequate to build up environmental databases relevant for global environmental issues involving time scales of decades to centuries.
- Archiving - building long-term time series: proper data archiving and the building of long time series is considered to be one of the most neglected aspects of environmental observations.
- Harmonisation, quality assurance, calibration/validation: the percentage of data not useable outside the local context due to lack in one or all these points is considered to be frighteningly large.

The partners in the development of the IGOS currently are the Committee on Earth Observation Satellites (CEOS), the sponsors of the G3OS, the programme offices of the G3OS, the International Group of Funding Agencies for Global Change Research (IGFA), the International Geosphere-Biosphere Programme (IGBP) and the World Climate Research Programme (WRCP). Additional partners are explicitly welcome.

Scientific support to policy-making has gained increasing importance in both the formulation of conventions and their supervision. Most often, the lack of sufficient data on the global environment is the main bottle-neck. The presently available monitoring systems are, though advancing rapidly, still not adequate to provide the required database. This was very recently emphasised by the "*Report on the Adequacy of the Global Climate Observing System*" to the Fourth Conference of the Parties (COP) of the UN Framework Convention on Climate Change (UNFCCC) (GCOS-48).

It should also be mentioned here that in its 1995 assessment, the Intergovernmental Panel on Climate Change (IPCC) emphasised the major uncertainties in our knowledge of the Earth system and its natural variability as well as anthropogenically induced change (Houghton et al., 1996). In particular, at decadal to inter-decadal time scales, our ability to separate natural from man-made variations is hampered by a lack of knowledge of system processes, an insufficient data base and methodological problems (see Plag, 1999, for a more detailed discussion). This supports the request of IGOS for data archiving and the building of homogenous long-term time series.

Some Requirements for the Virtual Network

Ideally, the design of a virtual network would be defined in order to provide products responding to clearly identified user requirements. Based on a thorough analysis of the "market", which as a result should identify all potential users (including future ones) of the network and their needs for specific products, a description of the user requirements should clearly specify the required properties of the products. These properties should be given in terms of availability, integrity, continuity, consistency, precision and accuracy. The design of the virtual network has to be such as to provide for these properties. This design process would also result in a set of specifications for the performance of the physical network and the quality of the observations provided by this network as well as the communication tools to be used.

However, over the last two decades the space-geodetic techniques have been in a state of intensive research and a very rapid development both in terms of accuracy, applicability and availability. Consequently, much of the development has been stimulated by ad-hoc responses to emerging needs and new potentials and capabilities. Within IAG, CSTG has provide some co-ordination (see e.g., Beutler et al., 1999), but very little was and possibly could have been done to bring forward a clear or even integrated strategy for building space-geodetic networks and services. The space-geodetic networks developed under IAG were and still are science-driven.

Prompted by the success of the IGS, other science-driven space-geodetic networks are currently in a phase of a reorganisation, which led to the establishment of several mono-technique services. Similar to the IGS, these new services focus on fostering the specific technique, the quality and availability of the data products, and partly the co-location with other techniques.

The design of a virtual network also strongly depends on the associated institutional network. In particular, the design can be modular or uniform, hierarchical and top-down or more democratic and bottom-up. For a network owned by a single institution or an organisation, a hierarchical structure with clear competence for decisions and delegation of work may be appropriate and most efficient. However, for regional or global networks it is hard to imagine a physical implementation which is not bottom-up and to a large extent depending on the voluntary contributions of the actors.

A service based on voluntary contribution is characterised by

- relatively high fluctuation of contributors and support;
- inconsistencies in observations, meta-information, and, eventually, products;
- relatively high probability of errors;
- unequal and time-dependent performance levels of different contributors;
- slow and/or insufficient response of contributors to requests from the network.

The design of the virtual network has to account for these deficiencies. In particular, the necessity of a comprehensive network monitoring and quality control is obvious. Therefore, regional to global monitoring networks should integrated these elements as part of the design of the virtual network.

The Earthwatch strategy requests as a design principle that it should not be allowed that data are cut off from their sources and collected in secondary locations where they can go out of date. To follow this principle puts a high demand on the data archiving facilities incorporated in the design of the virtual network. In particular, since data archiving only makes sense if the archived data are consistent, the virtual network has to assure the consistency of data and products.

Comments on the Institutional Network

Meteorological and some hydrological observations are the very few examples of user-driven observational networks, which have been operational for several decades if not centuries. Only recently, a rapidly growing number of operational global or regional monitoring systems have been established within the Earthwatch framework. These systems serve the increasing demand for environmental information in "early warning" as well as for the building up of environmental databases of the changing planet.

It is important to note that all these systems are institutionalised in a different way than the voluntary science-driven networks prevailing in geodesy. While the former ones are initiated through intergovernmental processes with a strongly formalised sponsoring, are the latter ones to a large extend based on voluntary contributions and the availability of budgets of single individuals and their institutions. These networks are mostly supported with scientific recognition by IAG and/or IAG commissions.

It is interesting to note that many of these science-driven voluntary networks have demonstrated an extreme ability to survive for a long time and to develop a long-term stability. Nevertheless, the establishment of an environmental monitoring system providing both long-term consistency required for global change monitoring and near real-time applications with considerable consequences in case of failure to meet the specifications, might require a different approach.

Are There Consequences for IGS?

If it is correct to interpret IGS's claim for "Monitoring Global Change by Satellite Tracking" as a quest for direct or indirect contributions to the rapidly developing global environmental monitoring and assessment programme, then it can be recommended that the IGS focuses some more attention on a few central issues.

If IGS intends to contribute in one way or another to the monitoring of global change for use in the broad context of environmental assessment, then the adherence to a globally accepted strategy in the design of the service, the maintenance of the databases in agreement with the global strategy, the linking of IGS's databases to other relevant databases, and the supply of high-level products within an integrated environmental information network are issues to focus on. This must not be misunderstood as if IGS would have to develop all this by itself. Rather, to achieve such a contribution, IGS needs to develop and maintain an awareness of the global development in Earth observing and to build up or strengthen the interaction with relevant scientific and societal programmes and services.

It appears to be of major importance to interact with programmes such as the G3OS outside of the traditional IAG and IUGG environment. Following the notion of Earthwatch that delivery of information products will most often focus on specific issues, IGS might once more take a lead and show how space-geodetic techniques with their high potential in data collection can contribute or even be integrated in information delivery systems focusing on specific environmental issues.

Of course, due to the rapid global development (which was only very briefly touched upon here), this may easily develop into a vast task. It is therefore recommended that IGS approaches this aspect of "Monitoring Global Change" with great care but nevertheless in a clearly articulated way. A first step could be to trace existing and investigate potential new links between IGS and, e.g., the G3OS. Furthermore, the comparison of IGS's internal strategies to the emerging ones for global observing and information distribution could help to identify discrepancies and to adjust IGS's future development accordingly to minimise the discrepancies.

Another, most likely more difficult issue is the question of how to handle the deficiencies of a voluntary-based service. It could be worthwhile to work out ways and methods to strengthen or even formalise the commitment of the different actors to the service.

The issues mentioned here are mainly related to the virtual and institutional networks but might eventually have consequences for the physical network, too.

It should be kept in mind that the strong support for global integrated monitoring expressed recently at the Fourth COP of the UNFCCC very likely will result in a re-directing of national funding of observational infrastructure (see the document COP, for instructive reading). Those who do not want or do not demonstrate that they are valuably contributing to a global integrated monitoring of the Earth system might loss in this process.

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Real Time Applications: A WADGPS Perspective

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The definition of real-time depends on the application. For some real-time applications using the IGS network, such as ionosphere and orbit estimation processes, it would suffice to have data collection epochs every 5 minutes with the data latency of up to 15 minutes. A more stringent real-time application is that of a wide area differential GPS (WADGPS) system. This application is stringent in that it demands high data sample rates (1 to 2 seconds), low latencies, and high data availability. Generally, if you can satisfy the needs of the WADGPS you will satisfy the needs of most real-time applications.

Satloc, a GPS applications company based in Scottsdale Arizona, has developed a WADGPS network providing DGPS coverage over much of North America. Differential corrections are delivered through a geostationary satellite broadcasting at L-band, enabling reception of both GPS and differential from a single antenna . Making use of key software licensed from Jet Propulsion Laboratory (JPL), this network became operational November 1996 and has achieved sub-meter real-time user position accuracies with 99.997 % availability. Satloc's approach to the ground-segment of this network, particularly in the localized distribution of data, may prove valuable for the IGS real-time network.

Satloc's Network

Satloc uses TCP/IP over frame relay as the data communications protocol. The remote GPS sites are equipped with Ashtech Z12 receiver, CSU/DSU/Router, UPS, and a Digital Equipment Corp. terminal server. The terminal server provides a reliable, low cost means of converting the RS-232 output of the GPS receiver to TCP/IP. See reference (1) for a more detailed description.

Satloc has built redundancy into their network by independently delivering tracking data to two separate Network Hubs which are geographically separated. At the Network Hubs, the data is gathered, reformatted into packets pertaining to the current epoch, and then broadcast across a local Ethernet to all listening applications. Applications such as orbits, clock, and ionosphere run on separate computers on the network, but all have access to the same real-time data.

Data Distribution

For a real-time network, the greatest flexibility would be achieved by allowing direct access to the real-time data by individual organizations. The problem facing the IGS will then be the distribution of the real-time data to the various users. Obviously, providing each user with a connection directly to the source of the GPS data is not feasible from a cost or reliability standpoint.

Rather than bring the data to the user, it makes more sense to run the real-time applications at Regional or Global Data Centers. The approach, taken by Satloc, of collecting the remote data and then broadcasting it over a local Ethernet network to listening applications is one potential strategy. The speed of local Ethernet is sufficiently high that UDP (user datagram protocol) broadcast of the data rarely result in collisions or loss of data. Software running on computers connected to this network then pick up the data and process it, returning the results back to a user, perhaps in a different part of the world. There are 3 advantages to this approach.

1. Although the bandwidth required to collect the raw GPS data may be high, it is quite likely that only minimal bandwidth would be required to transmit the results of the real-time application back to the end user. An example may be a map of ionosphere total electron content (TEC). Dial up Internet connections are likely to be adequate for an end user to obtain his/her results. Servers existing at the hub could be configured to route the results over the Internet.

2. By broadcasting the data on the local network, any computer connected to the network can have access to the data. Thus, the approach is computer and operating system independent, with the only requirement being that the real-time application is capable of receiving UDP broadcasts. The real-time application developer could choose the computer platform.

3. Many different real-time applications could have access to a large pool of GPS data without paying for bandwidth required to bring the data to the application. The approach is almost limitless in the number of applications which could run on this network.

There are of course some drawbacks. With UDP broadcasts, there is always the possibility of missed messages. At Satloc, we have not found this to be a problem. Our software is designed with this in mind and occasional missed data packets are not an issue.

Another drawback is that the real-time application would likely be developed without a connection to the network hub. To aid in this development, data from the network could be archived to CD-ROM and a utility could be used to play the data back as though it were real time. This is exactly what Satloc did to aid in some of their off-site development.

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