

**IGS**

**SESSION 9:  
PRECISE ORBIT DETERMINATION**

## Session Description

Chairs: H. Boomkamp, R. König

The future POD requirements for IGS will be different from those of the past 10 years in several ways:

- There will be many more IGS stations
- There will be many LEOs
- There will be more navigation satellites of interest
- Data will be available at higher rates
- Data will be available in (near) real-time

The above means that the demands on IGS POD in terms of number of input data and number of output products may increase concurrently with shorter latency and higher accuracy demands on the products. This asks for the analysis of recent and innovative algorithms.

Contributions are invited that address the following issues:

- Methods for processing substantially more data in a single IGS POD process, e.g. allowing data from more stations, more GNSS satellites, LEO satellites, or high-rate data Methods for reducing the latency of IGS POD.
- Real-time POD versus ultra-rapid predictions.
- Integrated POD of GPS, GLONASS, GALILEO and LEOs with mixed data types.

In general, contributions are sought that address the topic larger, faster, better POD.

## Session Summary

H. Boomkamp

The central theme of this session, as discussed in the Position Paper, were the conflicting tendencies towards larger IGS POD processes, shorter latencies, and increased product precision. Most IGS Analysis centres are operating near the limits of their computer resources, and can only increase process sizes or reduce latencies by improving computer hardware. Nonetheless, the future processing capacity requirements of IGS will increase substantially, notably due to the arrival of large numbers of GNSS satellites (Glonass, Galileo), larger station networks, and the arrival of LEO satellites. Presentations in the POD session all covered a particular aspect of coping with large process sizes or shorter latencies, while improving or at least maintaining present product quality.

In continuation of the position paper discussion, Henno Boomkamp presented new developments at ESOC in double difference data processing, aimed at including LEO satellites in standard IGS processes. By using high-rate double differences in combination with normal low-rate undifferenced data in the same process, the problem of having to solve for high-rate clocks is avoided.

Rolf Koenig presented GFZ activities in the area of combined solutions for GPS and LEO satellites. After a summary of typical POD process sizes at GFZ IGS Analysis Centre, some cases that included LEO data from CHAMP were presented. The estimation of Earth Rotation Parameters seems to benefit from the inclusion of the LEO data, although the current results provide only a preliminary insight in this matter due to the relatively small number of ground stations that can be included.

Urs Hugentobler showed how the POD set-up at the CODE Analysis Centre copes with large station networks and routine GLONASS processing. By breaking down the station network in several smaller clusters, the amounts of difference combinations and their global coverage can be controlled. Thorough pre-processing helps to reduce the main processing workload. Good reasons for larger station networks and inclusion of more GNSS satellites in a single process exist, and the increasing process size can be largely handled by changes at algorithmic level.

Jan Douša gave a thorough overview of the Ultra-Rapid and UR-prediction set-up at the GOPE Analysis Centre. By saving normal equations in batches, and re-using these batches in subsequent runs, the processing load can be reduced substantially: only a new batch has to be added, while the oldest batch is discarded. This leads to an efficient process in which only the most recent input data has to be processed completely, while the actual solution arc (s days) can be much longer than the interval between processes (3 hours).

Tom Herring presented the processing set-up at the new MIT Analysis Centre, which handles a large station network consisting of four partially overlapping clusters of 40 stations each and 148 stations in total, with a main interest in global clock solutions. Specific analysis was presented on how receiver clock quality influences the ambiguity fixing capability, and how anomalies with specific station receivers or satellites show up in the combination analysis, underlining the value of the IGS combination strategy based on independent processing systems.

The session recommendations aim to summarize the need for larger processes at shorter latency, while not compromising IGS product quality. Although projected computer resources seem to be able to cope with projected processing requirements, it will be useful to increase awareness of the cost of processing, by collecting processing metrics in a systematic way. For some new applications, notably inclusion of LEO data, improvements in hardware will have to be accompanied from improvements at algorithmic level in order to enable future routine processing.



# Bigger, Better, Faster POD

Henno Boomkamp, Rolf König

## 1 Introduction: performance of IGS POD systems

The performance of a system can be defined as: the amount and quality of work that is completed within a certain time. For POD systems this performance is measured by

1. The size of the POD process of interest
2. The precision of the output POD products
3. The execution time within which this process is completed

Precision requirements as well as limits to execution times are essentially imposed on the Analysis Centres by the particular IGS combination solutions to which a POD process contributes: finals, rapids, ultra-rapids, and in the future possibly real-time products. Within the performance limits of an IGS Analysis Centre, the POD process size (1) is therefore typically a function of the required precision (2) and latency (3).

The performance limits of an Analysis Centre are defined by

1. The capacity of the available computer hardware
2. The efficiency of the available POD software

Developments in computer hardware have been remarkably stable, and have been predicted to remain like that for at least another decade [Fig 1]. In any case, the capacity of computer hardware can hardly be influenced by the IGS Analysis Centres, other than by ensuring that hardware is regularly upgraded to state-of-art systems.

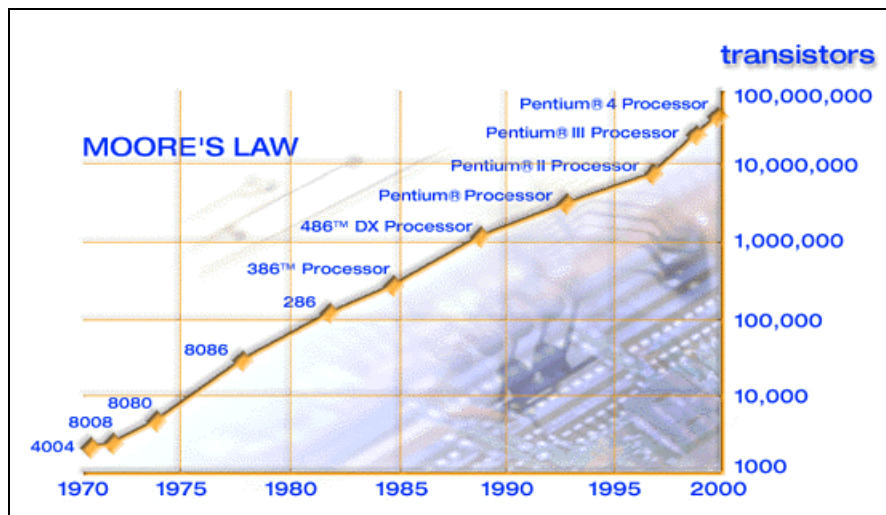


Figure 1: Developments in computer technology have been steady and predictable over the past three decades, as Gordon Moore already foresaw in 1965 [ref. 1].

The conclusion is therefore: any increase in process size, improvement in precision, or decrease in product latency, *beyond* the steady improvements that may be expected from developments in computer hardware, can only come from improvements in POD software: the Analysis Centres have no other means to influence POD performance.

After the first decade of IGS operations, it seems useful to investigate present and future developments in POD process size, precision and product latencies, and compare these against the expected improvements in computer hardware. This can provide insight in the capability of IGS to support expansions of its POD processes during its second decade of operations.

## 2 Bigger POD: expected developments in IGS process size

### 2.1 Process size parameters

The core of each POD system is an estimation process that computes a large number of model parameters from a substantially larger number of GPS tracking observations. The two fundamental size parameters of a POD process are therefore

$N_{obs}$	The amount of tracking observations that are processed
$N_{par}$	The number of parameters that are estimated

For a batch least-squares estimator, the dominant POD workload is the accumulation and inversion of a normal matrix from the observation equations. For a POD system based on a sequential filter, the workload of updating and inverting (more but smaller) state transition matrices is equivalent.

The parameters  $N_{par}$  and  $N_{obs}$  are both a function of 3 more tangible size variables:

$N_{GNSS}$	The number of GNSS satellites included in the POD process
$N_{sta}$	The number of ground stations included in the process
$N_{LEO}$	The possible inclusion of one or more LEO satellites in the process

A fourth size parameter would be the amount of observation epochs in the solution arc (i.e. the product of arc length and data rate) but this parameter is typically chosen in such a way that the required precision level is ensured for the case of interest. In other words, it is not really an independent parameter but is a quantity that is minimized as a function of the required POD outputs.

The workload for processing the normal matrix or state transition matrix grows essentially as a quadratic function of  $N_{par}$  and as a linear function of  $N_{obs}$ , while these two fundamental parameters grow as linear or quadratic functions of each of the three parameters “ $X$ ”, with  $X = N_{GNSS}, N_{sta}, N_{LEO}$ . The result is that the POD processing time is typically a cubic function of the parameters “ $X$ ”:

$$T = C_0 + C_1X + C_2X^2 + C_3X^3$$

The four coefficients  $C_i$  are difficult to determine for any individual POD system, but certain qualitative assessments can be made. For instance, even if the cubic component is small relative to the other two, it will inevitably start to dominate the function  $T$  from certain large values of  $X$ . This implies that all POD systems tend to have a fairly well-defined value for values of  $X$  that still be handled, namely, the point at which the cubic component in  $T$  starts to rise sharply. Further increases of the variable  $X$  will rapidly lead to prohibitive processing times, or memory problems.

To investigate current and future limits of POD processing, the expected increase of the process size parameters  $N_{GNSS}, N_{sta}, N_{LEO}$  can be quantified for the years to come.

## 2.2 Number of GNSS satellites in the POD process

**GPS** Although the nominal GPS constellation consists of 24 satellites, the number of operational satellites is currently 28. This number is expected to remain stable, also during the upgrade towards the next generation GPS satellites.

**GLONASS** There are now 8 operational satellites while 3 further spacecraft have been launched in December 2003. The official policy remains to reach the complete constellation of 24 satellites within a few years [ref. 2].

**GALILEO** Apart from one or more early satellites for commissioning purposes the 30 operational Galileo satellites are due for service by 2008 / 2009 [ref 3].

Conclusion: even if no further GNSS satellites are considered to be of interest to IGS (e.g. EGNOS geostationary satellites or possible Asian GNSS developments), the number of GNSS satellites will nominally grow to a total of 82 within the next five years [Fig 2].

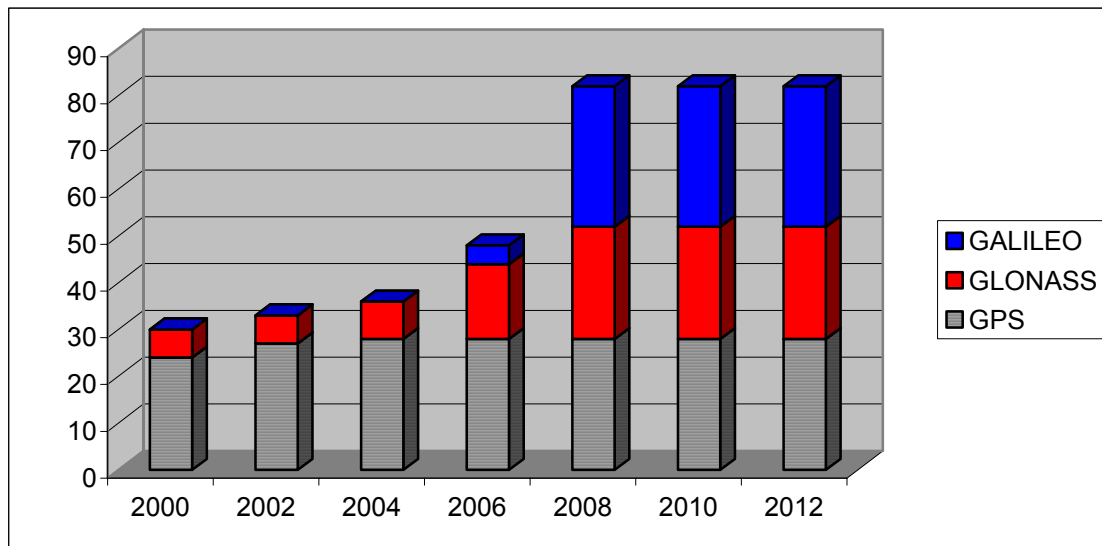


Figure 2: Future expansion of number of GNSS satellites, expected to increase sharply around 2008 to a new stable value of 82 satellites of interest to IGS.

## 2.3 Number of ground stations in the POD process

The increase of the number of IGS ground stations with time has been substantial, and is likely to continue in the years to come. None of the analysis centres would in fact have the capability to process all current IGS stations in a single POD solution, but this is neither necessary, nor is it desirable for reasons of solution independence. For the SINEX combination products, IGS sets certain requirements towards the number of input estimates for that station or to geographical distribution of the solution networks. The number of station positions that should be estimated by any single Analysis Centre can be estimated from

$$N_{est} = \frac{N_{required}}{N_{AC}} N_{total}, \quad \text{with:}$$

- $N_{est}$       Number of station position solutions that needs to be included in the POD process of a single Analysis Centre, on the average
- $N_{required}$       Minimum number of input solutions to produce an IGS combination solution for that station
- $N_{AC}$       The number of Analysis Centres that produce station coordinates
- $N_{total}$       The total number of IGS stations for which combination products are desired.

Current values for these terms are something like  $N_{required} = 3$ ,  $N_{AC} = 8$ ,  $N_{total} = 350$  so that on the average an Analysis Centre should produce solutions for 130 stations.

Not all estimated station positions need to be included in the actual POD process: some centres produce POD solutions based on a sub-set of stations and then estimate station coordinates for a larger set from fixed GPS orbits and clock solutions. However, to ensure reliable and consistent solutions a “reasonable fraction” of these  $N_{est}$  station coordinate solutions should be estimated in a single solution with the GPS orbits and clocks. A fairly arbitrary value of 50% will be considered here as “reasonable” - the actual percentage depends on many factors that fall outside the scope of this paper.

Conclusion: the number of stations that an Analysis Centre needs to include in a POD processes can be estimated as about 15 to 20 percent of the complete IGS station network. Figure 3 shows a projection of this quantity to the future. An alternative approach to cope with increasing numbers of ground stations is to have more Analysis Centres: the number  $N_{est}$  is inversely proportional to the number  $N_{AC}$ .

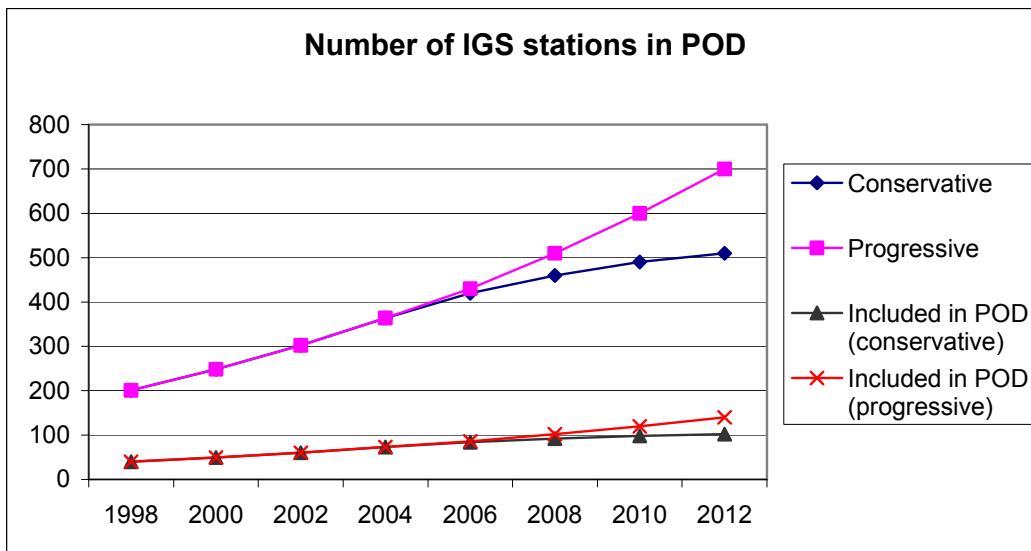


Figure 3: Conservative and progressive estimates of future increase in the number of IGS stations. The 20% lines at the bottom indicate the average number of stations that will have to be included in the POD processes of an Analysis Centre.



## 2.4 LEO satellites

The main impact of processing LEO and GPS satellites in a single POD process is the necessity to use higher data rates for the LEO than what is typically used for the GPS-only POD solutions. Precise GPS orbits can comfortably be determined using one observation epoch every five minutes, but a LEO may require data intervals of 30 seconds or less. To obtain adequate clock solutions and phase ambiguities, the clocks for the GPS satellites also need to be solved at this high data rate, and in turn the clocks of the ground stations are required to find the GPS satellite clocks.

The result is that for a given arc length the tracking data volume  $N_{obs}$  can grow by about one order of magnitude (e.g. data intervals reduce from 300 seconds to 30 seconds) just by including a single LEO satellite. Adding a second or third LEO would not have such a dramatic effect, because the same high-rate GPS and station clocks will be needed as for the first LEO. Depending on how clocks and ambiguities are solved, the number of estimated parameters may also increase substantially with the inclusion of a LEO.

Although LEO data does not yet form part of routine IGS processing in any way, the number of LEO satellites that may be considered for processing will be growing steadily in the next decade [Fig 4].

The main impact on a POD process is the step of including a first LEO. This can augment the size of the POD process by one order of magnitude. Once that a single LEO is included, further LEOs can be added at modest cost in terms of process size.

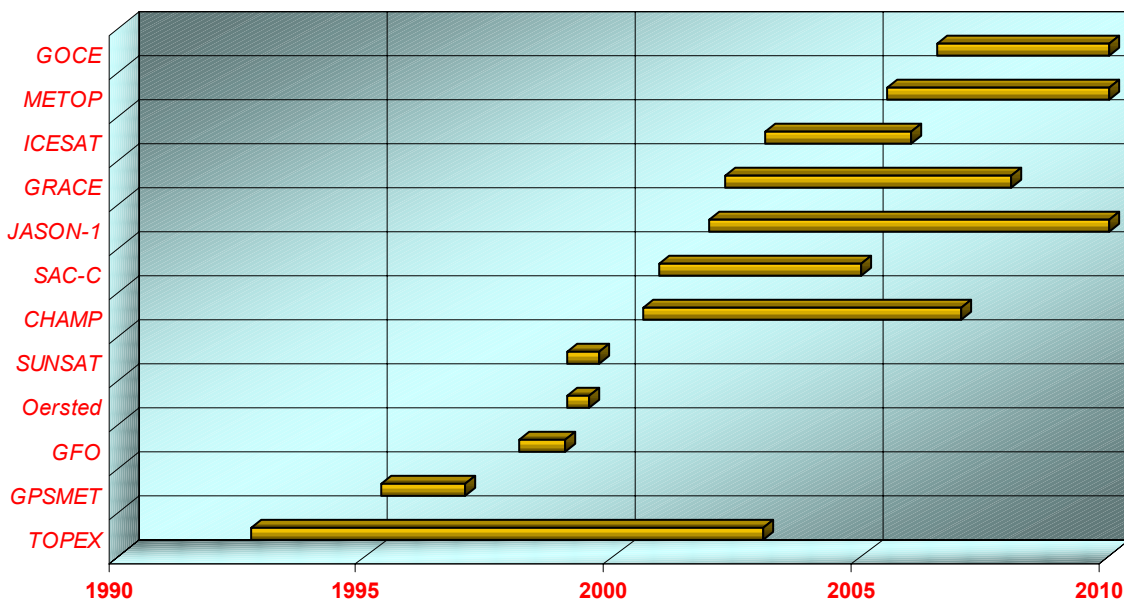


Figure 4: The launch of CHAMP marked the start of a new era of LEO satellites with precise GPS receivers

## 3 Better POD: precision of output products

The precision of the current IGS POD products is extremely good, and sets the standard in many areas of space geodesy. Nonetheless it will be a continuous ambition of IGS to improve the quality of its products to the best that can be achieved within the limits of state-of-art knowledge.

In general, improvements of POD product precision can come from three sources:

- Improvements of existing models
- Inclusion of new models for previously un-modelled error signals
- Improvements in observability of estimated parameters, by using more data per estimated parameter (e.g. longer arcs, higher data rate, more stations).

Modelling improvements (1) are mainly limited by state-of-art in scientific knowledge. The impact of such improvements on POD processing times is modest, for instance, a re-calibration of a set of antenna phase patterns does not necessarily augment the work of evaluating these models.

Given the already complex sets of POD models that must be evaluated, a newly added model must really be very complex or elaborate to have a notable impact on POD processing times. Any increase will typically be due to additional model parameters that need to be estimated.

The third source of improvements is clearly the most costly one, and is in fact the main motivation behind the steady increase of POD process sizes as discussed in section 2. The main reason for wanting “bigger” POD processes is of course to improve the observability of one or more IGS products. Examples can be:

- Densification of the station network can be expected to improve the reference frame and ionosphere products
- Inclusion of more stations and GNSS satellites in a single solution improves the separability of clocks from orbits
- Combined POD solutions for GNSS + LEO together with other data types can improve orbits and reference frame

The two subjects of “bigger” and “better” POD are therefore closely related, in the sense that IGS hopes to improve the POD products by increasing process size variables like the number of stations, or the inclusion of LEOs. The price to pay for these improvements can therefore be derived from what was discussed in section 2.

#### **4 Faster POD: short-latency and real-time processing**

The concept of producing separate solutions in the form of IGS Finals, Rapids and Ultra-Rapids already illustrates a fundamental incompatibility between achieving high product precision and low product latency. However, the precision of the rapids has been approaching that of the finals over the last few years [Ref 4]. With the arrival of real-time IGS station networks the datasets that are available for rapid or ultra-rapid solutions are now substantially larger than what they used to be by the time of introduction of these products.

There are two typical methods to provide real-time POD products:

1. Orbit and clock *predictions* are produced by a conventional POD process, and are frequently updated to ensure that they always remain within appropriate error limits. The impact on POD processing is a reduction of product latencies with respect to current IGS practice, combined with a larger number of POD processes to be run.
2. “True” real-time processing, in the form of a filter that converts an incoming real-time data stream into a real-time output stream of POD products.

On closer inspection, these methods are not fundamentally different because both approaches form a continuous stream of output products in time. The essential difference is that in approach (2) the discrete time output steps match the discrete time input steps, while in approach (1) the output steps are larger than the input steps. The first method can in principle be used with all existing POD systems, if computer capacity allows it, while the second method would require new software developments at most Analysis Centres.

Conclusion: Assuming that current IGS POD systems would be applied for real-time processing (method 1), the generation of real-time POD products will have the effect of reducing POD process latencies and increasing the number of POD processes. These effects can not be quantified very well but depend essentially on the prediction quality of the POD models and the desired real-time product precision.

## 5 A benchmark test: EGNOS

During the design phases of the EGNOS POD system, feasibility tests were performed around four existing, state-of-art POD systems. These tests form one of very few known comparisons of this kind between different POD systems. A reasonable quantification of the future capabilities of IGS POD systems will be made here, by extrapolating the main performance characteristics of the EGNOS POD system (all of which are in the public domain):

- The main POD process for EGNOS includes the nominal constellations of GPS and GLONASS ( $2 \times 24 = 48$  GNSS satellites) and is dimensioned for using 60 tracking stations. The separate processes for GEO satellites are not considered here [Ref. 6].
- The computer hardware for the EGNOS operational platform was consolidated before the implementation phases started, and is known to adhere to 1999 standards [Ref. 7].
- The EGNOS precision requirements meet the standards of [Ref 8].

Using the above information, performance comparisons with EGNOS could be repeated by any of today's IGS Analysis Centres in a fairly straightforward way, e.g. by extrapolating solutions with 12, 16, 20, 24, 28 GPS satellites to the case of 48 satellites, and relaxing orbit precision to EGNOS levels by reducing arc lengths or data rates. The main benchmark results of the EGNOS tests may therefore be stated here even without the luxury of having a clear reference: IGS-like POD systems need at least about 12 times the CPU and about 20 times the memory that is available to the EGNOS system.

Memory is hardly as critical to IGS as it is to EGNOS, so only the CPU times will be considered here. Fitting a straight line through the data points in Figure 1 shows that a factor 12 in CPU performance will be achieved after about 8 years of hardware developments. From this, it can be estimated that progress in computer hardware alone will allow IGS-like POD systems to run a real-time POD solution of EGNOS-size around the year 2007 or 2008.

This benchmark case relates to relaxed EGNOS precision levels, and IGS product precisions must be substantially better. This would inevitably imply longer product latencies for IGS (e.g. longer arcs, higher data rate), or smaller real-time process sizes by the year 2007. However, it is still useful to compare the EGNOS POD task (48 GNSS satellites, 60 stations, no LEO) directly to the expected IGS POD process sizes by the year 2007:

- From Figure 2: there may be 82 GNSS satellites to process, rather than just 48
- From Figure 3: the average Analysis Centre may have to process 90 to 100 ground stations, rather than just 60
- From Section 2.4: The inclusion of LEO satellites may augment the POD process size by one order of magnitude (...equivalent to another 6 years in CPU development)

The disconcerting conclusion of the benchmark example is: hardware improvements alone may not bring the performance improvements that are needed to keep up with the growth in IGS POD process sizes, and the desire to reduce latencies towards real-time processing.

## 6 Summary and discussion

This position paper, in combination with the various presentations in the Berne POD session, intends to provide insight in the relations and contradictions between POD process size, POD product precision, and POD product latency:

- The price to pay for larger process is typically an increase in latency
- The price to pay for improving precision is typically a larger process
- The price to pay for short latency is therefore: a smaller process, or less precision

An analysis has been presented of expected IGS POD requirements, expected hardware developments, and expected IGS POD capabilities. The conclusion is that future POD requirements may outgrow future POD capabilities by a substantial factor.

Two mechanisms that are available to increase IGS POD performance are:

1. Improvements in POD software efficiency (the EGNOS example shows what modern software engineering can do)
2. Increasing the number of IGS Analysis Centres, which especially reduces the number of ground stations that must be included by any individual Analysis Centre.

Points of discussion may be:

- The current IGS product range forms a reasonable compromise between “Bigger”, “Better” and “Faster”, but a re-evaluation of priorities between the three contradictive objectives may lead to an adjustment of the product range (process sizes, latencies).
- The extrapolation of future IGS POD capabilities in this paper is based on the one known example of EGNOS, and it clearly suggests that IGS POD requirements will substantially outgrow the capabilities of the POD systems in the years to come. It may be a good idea to organize a more direct analysis for the POD systems that are currently in use at the Analysis Centres, to confirm or deny this conclusion.
- The expected POD requirements assume that all relevant GNSS satellites and / or ground stations and / or LEO satellites will somehow have to be processed in a single POD solution, mainly for reasons of coherency of reference frames, clocks, etc. Methods to separate a large process into several smaller ones – without losing coherency - may be of increasing interest to IGS in the future. This can also complicate the combination solution process.

- IGS is fortunate to have welcomed two new Analysis Centres very recently, but further Analysis Centres would really be equivalent to an increase in POD processing capacity. Are there potential candidates for becoming an IGS Analysis Centre?

## References

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