# ACES Ground Segment functionality and preliminary operational concept

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***Abstract*— Atomic Clock Ensemble in Space (ACES) is a mission of the European Space Agency (ESA) based on a new generation of atomic clocks: a Cesium clock (PHARAO) based on laser-cooled atoms and an active Space Hydrogen Maser (SHM). The ACES clock signal will reach frequency stability and accuracy at the $10^{-16}$ level. Disseminated to ground via a dedicated link in the microwave domain, the ACES time scale will be used to perform comparisons with high-performance ground clocks. The payload will be operated in the microgravity environment of the International Space Station (ISS) and it is planned to be launched in 2013. The ACES Ground Segment (GS) will be integrated within the overall ISS ground architecture providing the communication links between ground and space through the Columbus Control Centre and NASA ground segment. ACES GS consists of two main components: the Users Support and Operations Centre (USOC) and a network of remotely controlled MicroWaveLink Ground Terminals (MWL GTs) distributed worldwide. The MWL GTs will interface with the ground clocks located at the laboratories and research institutes participating in ACES.**

**This paper presents the baseline architecture of ACES Ground Segment, its main functionalities and the preliminary operational concept. ACES GS Preliminary Design Review is planned for summer 2009.**

## I. MISSION OVERVIEW

ACES is a mission of the European Space Agency (ESA) based on a new generation of atomic clocks designed to be operated in the microgravity environment of the ISS. The ACES payload, so far one of the most challenging planned for the ISS, will be deployed on the external payload facility of the Columbus laboratory. The heart of the ACES system is constituted by two space clocks, the primary frequency standard PHARAO, developed by the French National Space Agency (CNES), and the active hydrogen maser SHM, developed in Switzerland. The performance of SHM and PHARAO are combined to generate an on-board ACES time scale with fractional frequency stability and accuracy of a few parts in $10^{-16}$. One of the main objectives of the ACES mission consists in maintaining a stable and accurate on-board timescale which will be used to perform space-to-ground as well as ground-to-ground comparisons of atomic frequency standards. The ACES clock signal will be transferred to ground by a time and frequency transfer link in the microwave domain, which compares the ACES frequency reference to ground clocks distributed worldwide, enabling fundamental physics experiments and applications in different areas of research. A GNSS receiver installed on the ACES payload and connected to the on-board time scale will provide Orbit Determination (OD) of the ACES clocks.[1,2]

A complete overview of the ACES mission, including reporting about current status, is presented in [3].

The ACES mission objectives are both scientific and technological. Amongst others, this mission is of great interest to two main scientific communities:

- The Time and Frequency (T&F) community; which aims to use ACES as a tool for high precision Time and Frequency metrology
- The Fundamental Physics community; which will benefit from the use ACES for accurate tests of general relativity

The ACES system comprises the ACES Flight Segment (FS) on-board the ISS, and the ACES Ground Segment (GS), including the MWL Ground Terminals which are connected to ground clocks. ACES science data is generated both on-board and on ground.

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The ACES GS will provide the monitoring and control facilities for the utilization of the ACES system and the services to the different categories of ACES users:

- Investigator Working Group (IWG)
- Scientific users
- Payload and instrument developers, for engineering support during the mission lifetime

The ACES GS will be integrated within the overall ISS ground architecture providing the communication links between ground and space through the Columbus Control Centre and the NASA ground segment (Fig 1).

The flight instruments are designed for a life-time of 3 years and the ACES mission is planned to run for a minimum of 1.5 years, with an instrument characterization phase of 3 to 6 months followed by the utilization phase.

The ACES GS is designed to provide the needed functionalities during the various mission phases:

- The pre-launch phase covers the period from the ACES payload (ACES PL) acceptance until the launch. During this phase, ACES PL will remain connected to an Electrical Ground Support Equipment (EGSE) which will provide adequate capabilities to deliver electrical power to the clocks ion pumps and basic monitoring functions. ACES GS operations are not considered during this phase although the overall ACES GS, including its MWL GT network, will be finalizing the mission operations preparation for both flight and ground science operations, including also the locally connected ground clocks and running cyclic tests to verify their overall behaviour.
- The launch and in-orbit transportation phase covers the period from launch to delivery of the ACES FS to its operational location as an external payload of the European Columbus laboratory. During this phase, ACES PL remains passive, except for the thermal control through dedicated power lines. The constraints induced by the vacuum maintenance at the clocks level will be monitored by the ACES GS.
- The in-orbit commissioning phase will cover the initial power-up and warm-up of the overall PL in order to activate all the instruments and support equipment. During this phase, full check-out and verification of the ACES PL including the instruments will be conducted. To verify the overall T&F transfer process commissioning tests will be run with the MWL GTs.
- The mission operational phase will cover the full on-orbit utilisation of ACES over its operational lifetime. This phase will be split into 2 parts: the characterization and the utilization sub-phases. The characterization sub-phase aims at the final commissioning, performance optimization and characterisation of the flight instruments under microgravity conditions. The utilization sub-phase aims at executing the various scientific experiment scenarios, for which the prerequisite is the operation of the flight instruments and space clocks at their optimum achievable performance. Space-to-ground as well as ground-to-ground clock comparisons will be performed. Ground clocks will be compared using both the common view and the non common view technique.

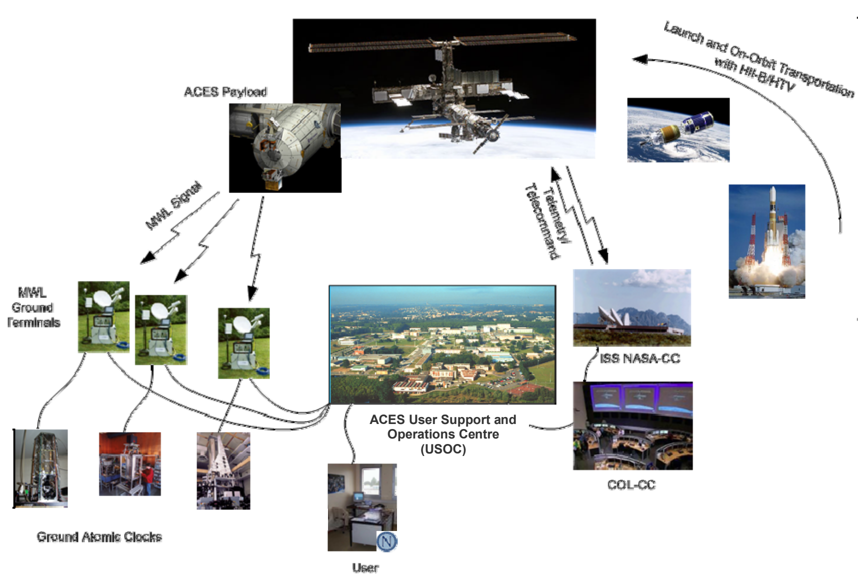


Figure 1. The ACES Ground Segment builds on existing infrastructure: ISS and Columbus Laboratory, the Japanese H2 Transfer Vehicle (HTV), NASA and Columbus Ground Segments and Control Centres, and the ACES Users Support and Operations Centre (USOC) infrastructure collocated at the CNES CADMOS centre in Toulouse (F)

## II. ACES Ground Segment Functional Description

ACES GS will provide all the elements and services needed to ensure the operation of ACES PL and the MWL GTs network, it will generate and archive the ACES scientific products making them available to the ACES end users.

ACES GS comprises as main components (Fig.2):

- The User Support and Operations Centre (USOC)
- Externally distributed facilities for Users, Payload Instrument developers and Precise Orbit Determination (POD)
- The network of MWL GTs distributed worldwide

### *A. ACES USOC*

The ACES USOC will be hosted at CADMOS (Centre d'Aide au Développement des activités en Micro-pesanteur et des Opérations Spatiales), located at CNES in Toulouse [4].

The ACES-USOC is responsible for the monitoring and control of the full system, providing all the operations preparation, execution and data management functions to run the mission. It comprises the following elements:

- Standard facilities common to other Columbus payload USOCs
- The ACES (Master) Operations Work-Station (WS)
- The ACES MWL Monitoring and Control Console
- The PHARAO Monitoring and Control Console as support to the instrument characterisation and utilization
- The ACES Archive server in charge of managing the archiving and retrieval of any data generated by ACES (flight segment, ground segment and MWL ground terminals) and the ACES Users
- The ACES Data Processing and Application server in charge of providing a set of applications shared by all the USOC working places as Product generation, Mission Planning, ACES, GS monitoring, etc
- ACES Data server located within a secure DeMilitarized Zone (DMZ) area that ensures decoupling of the external world and USOC internal area; while providing the external users with services, in particular it controls the access right to the data placed into the Data server. The DMZ area also ensures the access to ACES archive for data retrieval and it manages the communication flow with the IWG and the MWL GT network by transferring their requests to the respective USOC part
- ACES Mission Simulator used for operations preparation and troubleshooting during the mission

The ACES USOC will provide the users with services to access and use the ACES system, including web interface to guide and control the access of the different categories of users.

The following ground segment elements are located outside the USOC and interface with it through the DMZ zone:

- ACES IWG Console, providing ACES mission management requests and scientific management services
- Payload and Instrument developer WS, providing support during commissioning phase and for troubleshooting during nominal operations
- The Orbitography centre, getting ACES GNSS data from the USOC and providing OD information required for post processing and science products generation, and generating ISS orbit prediction data for MWL ground terminals operation

### *B. Network of MWL Ground Terminals (MWL GTs)*

The MWL GT network is responsible for connecting the ACES clocks to the ground clocks distributed worldwide. The network will comprise at least 7 terminals (plus one transportable unit), with the capability to accommodate up to 35 MWL GTs.

## III. ACES Ground Segment Architecture

### *A. Design Approach*

Fig. 2 presents the global architecture from the ACES GS and identifies the different barriers to ensure security management.

ACES USOC core is based on the Columbus Distributed Monitoring and Control System (CD-MCS) and together with the so-called High Rate Data Processing (HRDP) system provides all functions related to on-line monitoring and control, the mission database and the telecommand /telemetry storage. In the case of the ACES GS, the MWL GT network must be managed in addition to the FS, and the complexity of the instruments requires special scientific support during the different mission phases. This requires extending the capabilities of the standard CD-MCS for the management of ground-based elements which are distributed worldwide.

Basically, the CD-MCS provides ways to remotely connect external users through the User Home Base (UHB) concept which requires installing in each position a subset of the CD-MCS ensuring protocol and security management.

From an operations execution point of view, the working principle is to decouple the ACES FS operations, the MWL GS operations and the overall ACES mission monitoring and control.

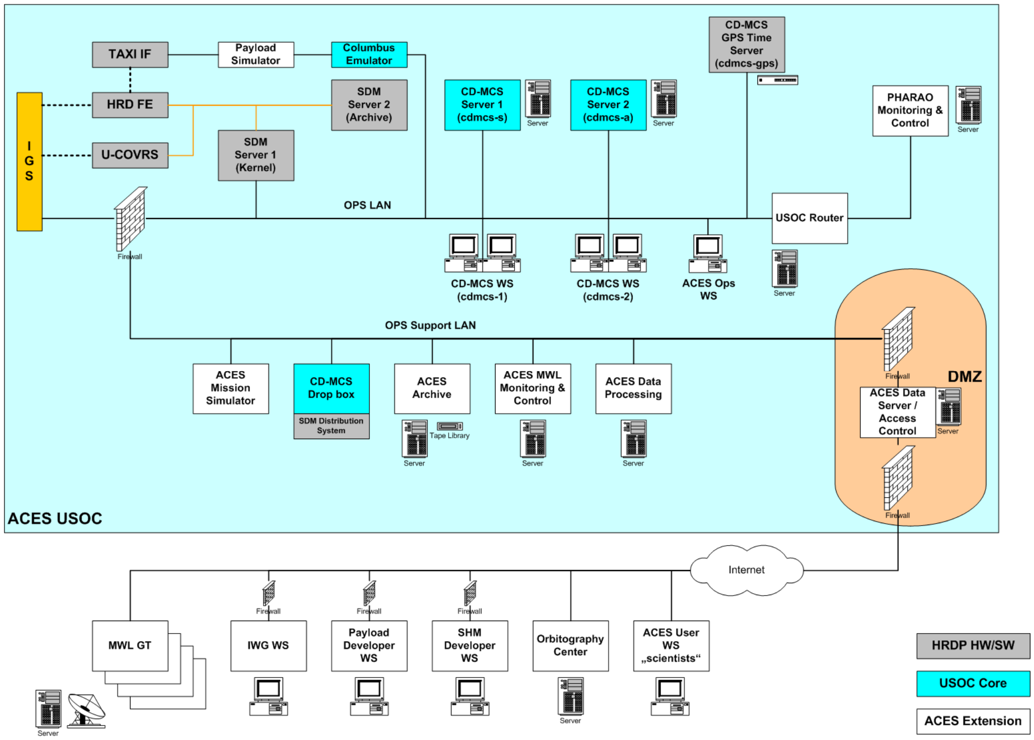


Figure 2. ACES Ground Segment preliminary baseline architecture

## *B. Architecture Components*

The USOC architecture concept clearly separates those facilities capable of interaction directly with the flight segment from support facilities or facilities not directly related to payload operations; the former facilities interface to the OPERATIONS LAN (OPS LAN) and the latter to the OPS SUPPORT LAN.

ACES USOC approach relies on extension of the OPS LAN and OPS Support LAN capacities by installing several elements, so called consoles, providing different functions.

The USOC Core together with the HRDP system gathers the components which are the basis of the USOC in the Columbus GS (Fig.2). It provides all the basic Control Centre facilities related to flight segment operations:

- ACES FS operations preparation and execution
- Command preparation: telecommand and timelines and command history database,
- Timeline preparation (verification and execution)
- Telemetry data archiving, L0 (raw data) and L1 data products (See data products definition in section VI)
- Telemetry data handling and housekeeping data evaluation
- ACES payload health and status evaluation
- The USOC Core provides common man-machine interface (MMI) for the ACES flight segment.

Connected to the OPS LAN are the ACES Operations and the PHARAO consoles. Connected to the OPS Support LAN are the MWL GT Monitoring & Control console, the ACES Archive, the Mission Simulator, and the ACES Data Processing and Application server providing services to the external users.

### *1) ACES Operation Console (ACES OPS WS)*

The ACES Operation Console is the ACES Master WS, in charge of control and management of the overall ACES mission. It will provide access to ACES FS and MWL GT status during the execution of this planning. This will be a control and monitoring position complementing the USOC core consoles for the effective control of the ACES elements.

### *2) PHARAO Console*

This console will provide PHARAO specialists (CNES/IWG) full access to PHARAO command and control; in particular it will allow the preparation of verification of micro-commands sequences to be validated. Commands are sent to the ACES operation console and routed to the CD-MCS WS for uplink via the standard Columbus command chain. Its main functions are:

- Monitoring and performance evaluation of the instrument
- Micro-commands and sequences preparation and validation

- PHARAO telemetry processing
- Preparation of PHARAO commands during the in-orbit commissioning for calibration and optimization, and during the mission operational phase for performance optimization and anomaly management

*3) ACES Data Processing and Application Server*

This server, located on the OPS Support LAN, shall provide the Data Processing capabilities to generate the ACES products L1, L2 and L3 from the incoming telemetry flows (ACES FS and MWL GT network). Besides data processing this server shall provide ACES USOC with services for mission and experiment planning, GS activities planning and planning execution monitoring. (See definition of ACES data products in section VI).

*4) ACES Archive*

The PL data (command and telemetry, including the instrument telemetry), ground generated data and derived parameters (i.e. parameters calculated on ground as resulting of data processing) will be processed and archived in this facility. This device will provide the capability to manage the ACES archives.

*5) ACES MWL Monitoring and Control Console*

MWL console is connected to the OPS LAN. It ensures the management of the MWL GT, including:

- Selection of the MWL GT according to experiment definition (e.g. clocks, location, …)
- Selection of MWL GT to optimize the number of clocks comparisons and type of clocks required per orbit
- Selection of MWL GT to optimize the quality of the visibility along the orbit
- Acquisition of orbit prediction data from the Orbitography centre and preparation of tracking files for the MWL GT contributing to the mission scenario
- Monitoring of MWL GT network by processing received housekeeping data
- Preparation of MWL FS visibility plan and definition of the sequence of MWL GTs to be connected to the MWL FS.
- Management of MWL GT network anomalies.

*6) ACES external applications server*

This server provides the external users the access to the system by fully controlling the data exchange and the access to the OPS LAN. It will be organized as an application server processing the requests of entities outside the USOC. These requests could come from the MWL GTs, IWG, PL developer, scientific user or orbitography server.

## IV. ACES Mission Operational Concept

From an operation concept point of view, the final instrument characterization and the Commissioning phase are involving the IWG team, the PL and Instrument developers for real-time evaluation and assessment of ACES FS performance and status.

During the mission, operations take place according to an execution plan prepared on ground.

Taking into account the communication restriction for the uplink, the operation concept is based on the preparation and uploading on a regular basis of the ACES flight segment timeline (e.g. ACES schedules, MWL workplan, PHARAO workplan), together with the ground dissemination of MWL GT tracking and schedule files for the ground terminals in the mission.

Operations will rely on the execution of these plans with the capability of the ground operators to intervene in case of anomaly or degradation of scientific performances.

## V. Microwave Link Ground Terminals

### *A. General Description*

The MWL is a two-way dual frequency system operating continuously with a carrier frequency in the Ku band. The high carrier frequency of the up- and down-link allows for a noticeable reduction of the ionospheric delay. A third frequency in the S band is used to determine the ionosphere Total Electron Content (TEC). The MWL system performs both code and carrier phase measurements and it is designed for multiple access capabilities. The network of MWL GTs will allow space-to-ground as well as ground-to-ground clock comparisons. In particular, comparisons of ground clocks down to the $10^{-17}$ frequency uncertainty level will be possible using both the common view and the non-common view technique. A detailed description of the MWL design is presented in [5].

MWL ground terminals will be located at sites and laboratories equipped with high performance clocks.

The installation of the ground terminals requires:

- A dedicated position for the MWL GT with free field of view for the MWL GT Antenna Unit (AU) (in general on a roof top),
- Continuous, stable power supply 230V AC,
- 100 MHz and 1 pps reference signal from the local clock,
- Access to a local network (LAN) and to the internet,
- Radio transmission and reception licenses

The MWL GT is a ground-based RF station interfacing to the ACES MWL Flight Segment (FS), to the ACES USOC, and to a high-performance ground clock located at the MWL GT site. The MWL GT antenna is 60cm diameter and it is equipped with a steering mechanism to follow the ISS ephemeris (Fig. 3).

Antenna and MWL GT electronics are protected by a radome cupola. All other elements outside the radome (Control PC, AC/DC converter, etc.) are accommodated in an outdoor cabinet .

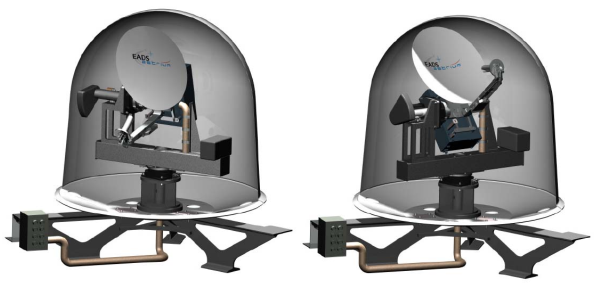

Figure 3. ACES MWL Ground Terminal: the MWL GT Antenna Unit (AU), the MWL GT Electronics Unit (EU) and the pointing mechanism are accommodated inside a radome and are thermally stabilised.

### B. *Electrical Interfaces*

#### 1) *Power Supply Interfaces*

The MWL GT will interface to local AC power sockets of 115 V/ 60 Hz or 220-230 V/ 50 Hz with a static current of 10A. The power input will be properly protected and fused.

#### 2) *Monitoring & Control Interface to ACES USOC*

The MWL GT will interface to local public LAN for data exchange (commanding & telemetry) with the ACES USOC via the internet. The local site shall ensure permanent availability of the internet connection to not constraint the MWL GT operations. The MWL GT is insensitive to short interruptions of the connection due to its automated operations; however, longer interruptions may lead to inaccurate orbit prediction (based on outdated ephemeredes), delay in telemetry transmission and could eventually impact the quality of the data generated. The MWL GT will be protected by a local firewall.

#### 3) *Monitoring & Control Interface to Ground Clock*

The MWL GT will provide data interfaces, serial RS422 / RS485 or LAN to receive housekeeping and status data of the Ground Clock. The LAN interface to the ACES USOC may be used also to interface the ground clock.

### C. *RF interfaces with the Ground Clock*

The MWL GT will interface to the reference signal provided by high performance ground clock. The ground clock reference signal shall meet the interface requirements shown in Table I.

TABLE I. PRELIMINARY RF INTERFACE REQUIREMENTS AT THE MWL GT CLOCK INPUT

| | |
|---|---|
| Frequency | 100 MHz |
| Waveform | Sine |
| Output | Single-ended SMA |
| Level | 6 dBm +/- 3dB |
| Level Stability | +/- 0.1 dBpp over one day |
| Spurious | Harmonic: < -70 dBm<br>Non-harmonic: < -70 dBm |
| Output Impedance | 50 Ω +/- 1% |
| VSWR | 1.15 |
| $S_{22}$ stability | 1.5 x $10^{-3}$pp over one day |

The ground clock RF interface is located on the MWL GT Electronics Unit and SMA connectors will be used.

Performances and present status of the ACES MWL are discussed in [3].

## VI. ACES DATA PRODUCTS AND USER ACCESS

### A. *ACES Archive*

Data and data products generated by ACES will be stored at the ACES Archive. This archive will be used by the scientific community at large in post-operations and by the ACES IWG both during operations and in post operations.

The physical location of the ACES Archive will be at the ACES USOC in CADMOS – Toulouse, protected by the CNES firewall. ACES data will be accessible to external users via web interface with search capability through the ACES Data Server. Details of the network configuration can be found in section III.

The ACES Archive will contain all the data telemetered from the spacecraft and the MWL ground stations, in both raw and engineering values, the telecommand history, the ACES database, as well as ACES data products (Analysis Objects), data analysis tools (with user manuals), ACES plans (operations plans, ground stations visibility plans, IWG experiment plans, etc.), and legacy documentation.

The archive interface design and, to some extent, the contents are currently under definition and will be kept flexible, extensible and responsive to feedback from the user community [6]. The interface for expert users will permit searches against queriable contents of the ACES Archive, ensuring enough flexibility.

The search interface will provide quick (i.e. a few seconds) feedback on the expected results of a query in terms of number of matching items. The results will be sortable according to customizable parameters (e.g. time, length of data taking, ground clock type, ground clock position, experiment type, etc).

### B. *ACES Data Products*

ACES Scientific Data Products are generated from raw measurements, based on analytic expressions (Fig.4).

ACES data products are classified as follows:

#### 1) *ACES Level 0 data products (L0)*

The ACES L0 data are the ACES PL raw data, ACES GS raw data and the required ancillary data after the following process: format synchronisation, decoding, de-multiplexing, time tagging in various time scales (ISS time, CDHU time, MWL time, UTC, TAI,…), sequence reconstruction, etc.

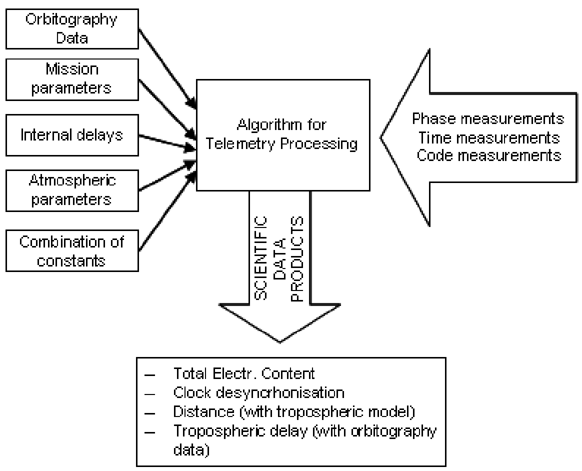


Figure 4. ACES data products generation process

The information contained in these products shall permit to rebuild the general context in which the products have been generated and to fully re-process the data, if needed. In particular, each instrument data shall be linked to the ACES general environment.

*2) ACES Level 1 data products (L1)*

L1 data products are the Level 0 products converted to engineering values and timestamped to the same time scale (UTC, GPS, TAI, ACES on-board time, etc.) and reference frame (ITRF preferred).

*3) ACES Level 2 data products (L2)*

ACES L2 data products are Level 1 data processed in 'near-real time'. They are mainly used to evaluate the status of the space clocks and provide a quick look data for monitoring the results of the space-to-ground clock comparison at the $10^{-15}$ uncertainty level.

*4) ACES Level 3 data products (L3)*

L3 data are the full performance results of the comparison between space and ground clocks evaluated down to the $10^{-16}$ uncertainty level on the basis of OD data.

*5) ACES Level 4 data products (L4)*

L4 data products are provided by the scientific community. They include:

Regular reports on the continuous comparison between the "primary" clock providing the reference signal to the ACES MWL GT and the "secondary" clocks eventually available at the User Ground Stations (UGS)

- Comparisons of the "primary" ground clocks via GPS, TWSTFT, etc
- Results of the analysis performed on L3 data to achieve the ACES mission objectives. Each L4 data product will include all the information necessary to identify the lower level data segments used for the analysis and for reconstructing the actual status of both ACES FS and involved UGSs

## VII. CURRENT STATUS

The Preliminary Design Review of ACES GS will take place in mid 2009.

The first MWL ground terminal will become available in autumn 2009 and the MWL end-to-end test between the MWL flight segment and the MWL ground terminal is planned to begin mid October 2009 [3].

The process to identify the locations of the MWL ground terminals will be initiated in 2010.

## ACKNOWLEDGMENT

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