Technical description of a novel sensor network architecture and results of radar and optical sensors contributing to a UK cueing experiment

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ABSTRACT

The Science and Technology Facilities Council (STFC), Control Loop Concepts Limited (CL2), Natural Environment Research Council (NERC) and Defence Science and Technology Laboratory (DSTL), have recently participated in a campaign of satellite observations, with both radar and optical sensors, in order to demonstrate an initial network concept that enhances the value of coordinated observations. STFC and CL2 have developed a Space Surveillance and Tracking (SST) server/client architecture to slave one sensor to another. The concept was originated to enable the Chilbolton radar (an S-band radar on a 25 m diameter fully-steerable dish antenna called CASTR – Chilbolton Advanced Satellite Tracking Radar) which does not have an auto-track function to follow an object based on position data streamed from another cueing sensor. The original motivation for this was to enable tracking during re-entry of ATV-5, a highly manoeuvrable ISS re-supply vessel. The architecture has been designed to be extensible and allows the interface of both optical and radar sensors which may be geographically separated. Connectivity between the sensors is TCP/IP over the internet. The data transferred between the sensors is translated into an Earth centred frame of reference to accommodate the difference in location, and time-stamping and filtering are applied to cope with latency. The server can accept connections from multiple clients, and the operator can switch between the different clients. This architecture is inherently robust and will enable graceful degradation should parts of the system be unavailable. A demonstration was conducted in 2016 whereby a small telescope connected to an agile mount (an EO tracker known as COATS - Chilbolton Optical Advanced Tracking System) located 50m away from the radar at Chilbolton, autonomously tracked several objects and fed the look angle data into a client. CASTR, slaved to COATS through the server followed and successfully detected the objects. In 2017, the baseline was extended to 135 km by developing a client for the SLR (satellite laser ranger) telescope at the Space Geodesy Facility, Herstmonceux. Trials have already demonstrated that CASTR can accurately track the object using the position data being fed from the SLR.

1. INTRODUCTION

The Chilbolton Observatory (Fig. 1), located near Winchester in Hampshire, Southern England (Lat. 51.145˚ N, Long. 1.438˚ W) is owned and operated by the Science and Technology Facilities Council (STFC). Staff at the Observatory develop and operate a wide variety of instrumentation to conduct observations to support research into meteorology and space. The Chilbolton radar, a high-power S-band system equipped with a fully-steerable 25 m diameter dish antenna, has hitherto been used for meteorological and atmospheric science research [1]. In 2010, this radar was modified for use as a space surveillance and tracking (SST) asset [2]. In this paper, it will be referred to as CASTR (Chilbolton Advanced Satellite Tracking Radar).

Fig. 1. Aerial view of the Chilbolton Observatory site

CASTR does not have an auto-track capability; hence it has to be pointed using *a priori* information to allow targets to be successfully detected. Typically, this information is provided by NORAD two line element sets (TLEs). CASTR has a high success rate of detection of satellites in LEO, however, the accuracy of a TLE can be compromised or invalid if the element is old, the spacecraft has manoeuvred, or it is in re-entry. During these cases, target detection cannot be guaranteed. In 2014, CASTR was used to track the final orbits of ESA's ATV-5 re-supply vehicle during its re-entry after undocking from the ISS. Without the auto-track capability, the tracking had to be de-risked using high fidelity ephemeris data provided by ESA, as the TLEs were not being updated quickly enough after the deceleration burns. During an uncontrolled re-entry, or one where the high fidelity ephemeris data isn't available, the spacecraft would be un-trackable. The desire to mitigate this risk without the expensive upgrade to a monopulse auto-track became the motivation to experiment with cueing the radar from another sensor which could lock on to the track of a spacecraft.

A suitable sensor must be able to resolve the position of the object being tracked and provide a timely stream of position data that can be streamed to the 25m antenna control server. The remote sensor could be another radar, an optical system, or a program generating predictions based on accurate ephemeris data.

In 2015, Control Loop Concepts Ltd (CL2), a tenant company at the Observatory, was working with an optical tracking system to develop software to enable tracking and trajectory recovery of terrestrial airborne targets. With guidance from STFC, they had already adapted their system so that it could track satellites, as they were ideal targets of opportunity with which to test their system. The slaving concept was discussed with them, and with funding from the Defence Science and Technology Laboratory (DSTL), CL2 were subcontracted by STFC to design and develop the communication protocol and software necessary to cue the Chilbolton 25m antenna in near real-time with a remote sensor. In March 2016, the 25m antenna and CASTR was slaved to an optical system co-located at the Observatory and successfully demonstrated to DSTL.

The first sections of this paper will identify the requirements of the system architecture, present design detail of the system, and describe how the system has been implemented. Additional sections will provide some technical details of the sensors used in the experiments. Results of the experiment will also be presented.

2. SENSOR CUEING REQUIREMENTS

Look-angle information is required to drive a sensor along a satellite track. To allow one sensor to cue or slave another, this information is required to be sent in near real-time. By near real-time, timeliness in the order of less than a second is generally required. The latency between transmission and reception over public networks is not very well controlled so some means of estimating this to allow latency correction is also required. Furthermore, if public networks are to be used, a high transmission rate is unrealistic. Continuous data rates in the order of 5 Hz to 10 Hz are readily achievable. Higher rates cannot be guaranteed over the public network.

For the reasons of cost minimization, and desire to avoid installation of additional infrastructure, the network will be assumed to be Ethernet and the Internet. This will be utilised for both on-site sensor connectivity, and for inter-site sensor communications.

Two way communications is required. TCP/IP will be used which guarantees message delivery, but not necessarily in a timely way. Pointing data messages will contain timestamps so latency, which is inevitable, can be compensated for at the receiver end of the link.

It is envisaged that after the initial link dialogue and a connection is established, the data source sensor will stream look angle data to the slaved sensor at a predetermined rate. However during the initial dialogue and at any time thereafter the slaved sensor site should be able to request other metadata needed for set up or information. A set of request messages as well as response messages will also be required therefore.

Accurate slaving will require that the timing used for the separated sensor systems is synchronised. All systems must be synchronised to UTC with accuracy commensurate with allowable tracking errors. In the case of the Chilbolton Observatory S-band radar, it has a beam-width of 0.25 degree and a maximum tracking rate of 2.5 deg/s. To maintain a track to within 10% of beam-width at maximum rate, timing errors must be kept below 10 ms.

The CASTR sensor will be configured as a server and the remote sensors as clients. This will allow security and access of the link to be managed by Chilbolton Observatory. It also means that there can in principle be multiple co-operating sensors and selection of which is to be used is more straightforward.

It is necessary to create a secure link between client and server. A security layer within the application software can be employed. The secure communication link set up means that potentially sensitive information is transferred safely.

It will be essential to ensure that the look-angle data from the source sensor is transformed, either at the client end, or the server end to compensate for the different physical locations.

The software implementation of the server and client software must include displays of sensor status and position information, and logging of critical data. The server needs suitable control functionality to select connected clients, and to interface with the antenna control system.

3. MIDDLE EARTH PROTOCOL

A sensor communication protocol was developed by CL2 and approved by STFC. This protocol (named the Middle Earth Protocol [MEP]) describes the format to convey the necessary information between two connected sensors and to stream the real time data between the remote client and the server connected to the 25m antenna. The protocol name comes from the nature of the axis transformations which use Earth Centred, Earth Fixed (ECEF) as the intermediate coordinate system. This name has led to a profusion of Tolkien character names to be used for components of the system.

The architecture has been designed to be extensible and allows the interface of both optical and radar sensors which may be geographically separated. Connectivity between the sensors is via TCP/IP over the internet. Time-stamping is applied to all packets to ensure synchronization, and to enable latency compensation. The source look-angle data can be in any of the following axis coordinate systems: RAE (Range, Azimuth and Elevation), ENU (East, North and Up), NED (North, East and Down), ECEF (Earth Centred, Earth Fixed), ECI (Earth Centred Inertia), or LLH (Latitude, Longitude and Height).

The data transferred between the sensors is translated into an ECEF frame of reference to accommodate the difference in location. Final conversion of the axis data to the azimuth and elevation axis system, as well as suitable filtering, latency and angular corrections to ensure smooth and precise tracking, are performed in the server. The server (called Gandalf) controls the 25m antenna. The server is programmed to constrain the antenna movements to those the antenna system is capable of performing. It can accept connections from multiple clients (currently up to 10), and the CASTR operator can switch between the different clients to take advantage of the best available data. Tracking based on NORAD TLEs is now conducted by connecting to a local TLE client called Olorin.

Network security is managed using a Transport Layer Security/Secure Sockets Layer (TLS/SSL) which has mechanisms for validating keys. The client is provided a key by the server system manager. The keys must be signed by an official public certificate authority. If either the client key or the server key cannot be validated by the opposite party, then the connection is dropped.

After a link between client and server is established, metadata associated with the look angle information must be available from the client, via the communication link, at the request of the server. These data will be requested and sent to the server:

- Sensor Site
- Sensor ID
- Sensor variant
- Sensor position
- Session ID
- Object being observed ID
- TLE (if appropriate)

The basic message structure comprises a message length, a protocol/data dictionary version, a session ID, the message payload and CRC bytes. There are many different message compositions that can be defined and created, including the metadata response message, look-angle data messages for each different axis system, and a null message for test purposes. In general, each message should always include time and a complete data set; for example x, y, and z in the chosen co-ordinate frame.

The Data Dictionary shall maintain a list of all message value definitions. The data dictionary shall contain all the keys necessary to pass information between the server and each sensor client. A master data dictionary is currently maintained by CL2, and made available by STFC. The first entry in the Data Dictionary shall be the protocol version number.

The MEP can support multiple servers, and one server can act as a client and connect to a second server. Fig. 2 is a block diagram of a conceptual MEP architecture.

The detail of the client design will depend to some extent on its purpose, and the sensor to which it is associated.

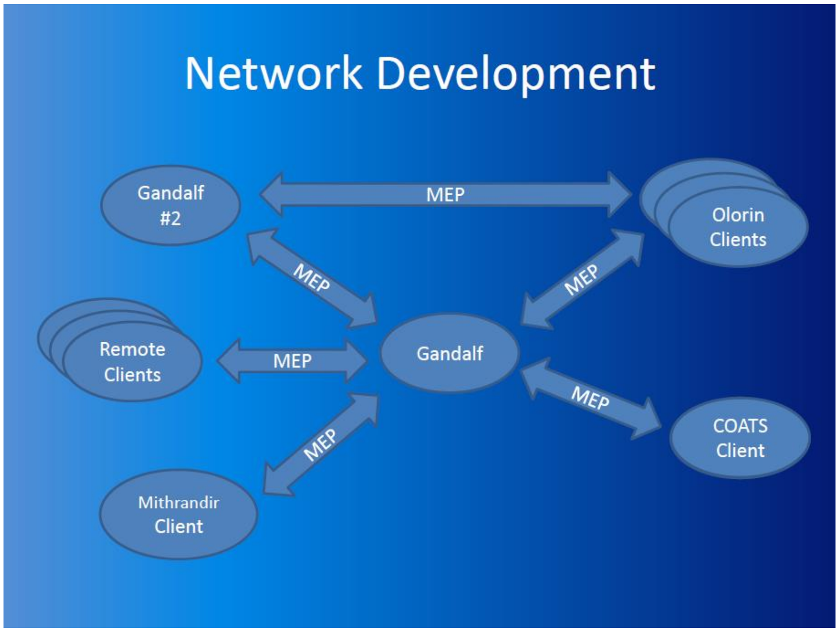

Fig. 2. Block diagram illustrating the MEP network concept

4. CURRENT CHILBOLTON MEP NETWORK

This section will describe the current sensors and clients that have been implemented on the Chilbolton MEP network. The current network architecture only uses a single server which is connected to the CASTR/25m antenna at the Chilbolton Observatory. Connected to the network are two additional optical sensors: COATS and SLR. Each of those sensors has a dedicated client, and additionally, one or more TLE clients are used to control the 25m antenna. A diagram of the current network can be seen in Fig. 12.

4.1 CASTR

CASTR (Chilbolton Advanced Satellite Tracking Radar) is an S-band radar mounted on the 25 m steerable antenna (See Fig. 3). The dish is a fully steerable elevation over azimuth mount, and is capable of tracking most satellites in LEO. Specification of the radar is detailed in Table 1.

Fig. 3. The 25 m diameter fully-steerable dish

A pulse repetition frequency (PRF) of 71.428 Hz, corresponding to a pulse repetition interval (PRI) of 14.0 ms and a maximum unambiguous range of 2100 km, was chosen so as to achieve alias-free range measurements for targets in low-earth orbit (LEO). Under these conditions, although the peak power is some 700 kW, the average transmitted power is only 25 W. The system's polariser was configured to transmit pulses of fixed, horizontal polarisation, while the radar's receivers simultaneously recorded both co-polar (horizontal, H) and cross-polar (vertical, V) target returns.

Table 1: Specification of CASTR sensor

Parameter	Value and comments
Antenna size	25 m parabolic reflector, prime focus feed
Azimuth	-90^o to $+450^o$ at 3^o/s Suitable for LEO apart from high elevation passes
Elevation	-2^o to 92^o at 1^o/s
Encoder resolution (both axes)	1/8th arcminute => 1/480^o
Tracking sources	TLEs, track files, client/server system
Operating frequency	3076.5 MHz
Antenna gain	53.5 dBi
Beamwidth	0.27° (FWHM; -3 dB, 1-way)
Polarisation	Tx: H; Rx: H and V
Transmitter type	Cavity magnetron
Peak power	700 kW
Average power	25 W
Pulse repetition frequency	71.428 Hz
Pulse width and coding	0.5 μs, un-coded rectangular
Receiver type	Superhet, log and I/Q channel
IF centre freq. and bandwidth	30 MHz centre, 4 MHz BW

CASTR has been used to conduct hundreds of satellite tracks (using TLEs) of more than a hundred different targets in LEO. It can detect objects out beyond 2100 km, and with RCS values greater than 0.5 m^2. The radar is capable of tracking day or night, and in all weather conditions.

4.2 GANDALF SERVER

The Gandalf server is the software program developed to implement the Middle Earth Protocol at the Chilbolton Observatory to interface with the CASTR 25m antenna. It runs on a Linux PC called Shadowfax.

The server embeds the following functionality:

- Generates and send commands to the antenna control system.
- Monitors the antenna encoder and status feedback.
- Responds to client connections.
- Displays antenna position and status information, a list of connected clients and details on the selected client.
- Provides command input capability.
- Allows the server user to select which client is to be used for position demands.
- Allows the server user to apply position and time offsets via the keyboard.
- Accommodates input demands in LLH, ECI, ECEF, ENU, NED or RAE axes.
- Performs the necessary axis transforms to convert the incoming demands into azimuth and elevation demands.
- Calculates latency and applies the required prediction to synchronise demand with the controller clock.
- Calculates position and velocity demand to feed to the antenna controller.
- Includes a security layer (SSL) for client connections.
- Produces a logged track file containing the antenna trajectory.
- Provides a log of critical data.

Fig. 4 shows the main screen of the Gandalf server display. The top region displays the 25m antenna information. The middle region shows the connected client information. The bottom region shows a list of the connected clients.

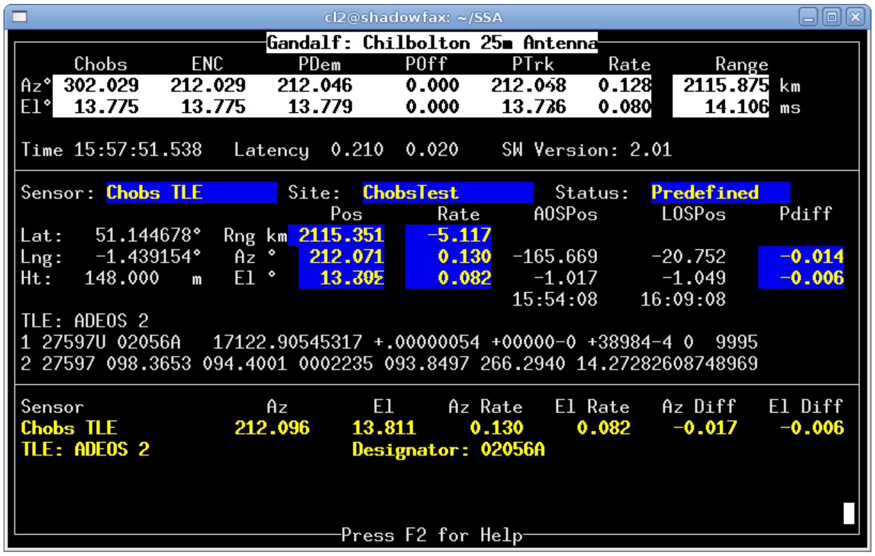

Fig. 4. Gandalf server display (main screen)

4.3 OLORIN CLIENT

The Olorin client is the software program developed to allow a track to be calculated and transmitted, from a user selected TLE. The TLE client allows the users to select a TLE from a list held in an associated TLE file. Fig. 5 shows the main screen of the Olorin client. The selected TLE is used to generate object x, y, z co-ordinates in real-time and transmit them using the Middle Earth Protocol. The timestamp is generated from the Linux clock on the local machine.

Multiple copies of the TLE client can be run simultaneously. This is useful because it provides more than one TLE client that can be selected in the server application. Different TLE files can be open in each client, and the operator can quickly select between the two. This is useful if there are variants on a TLE for a specific satellite, and there is a need to switch between them while tracking; possibly to identify the one which achieves the strongest radar return. Running Olorin at a remote site is feasible as well, and is an effective way of checking the network performance.

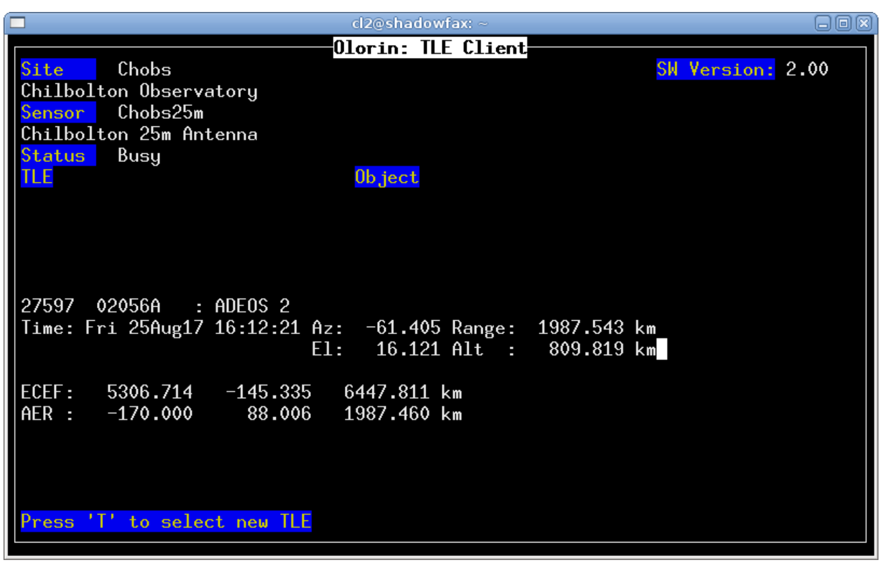

Fig. 5. Olorin client display (main screen)

4.4 COATS

The COATS (Chilbolton Optical Advanced Tracking System) sensor is a versatile EO tracking system that can be used for tracking and imaging all satellite regimes (LEO, MEO, and GEO). Fig. 6 shows the system with the 8" Ritchey-Chretien telescope, the Sony zoom camera, and the Samyang mirror lens. It is currently configured to be used a transportable system, hence is not enclosed within a protective dome. The technical specification is detailed in Table 2.

Fig. 6. COATS in the Chilbolton Observatory car park

The EO system needs to be calibrated to obtain accurate results. The identification process is carried out, in part using level sensors and an in-built auto-calibration function, in part by use of a terrestrial reference object and in part using stars. The terrestrial object is adequate to identify azimuth and elevation offsets and camera boresight skew. Thereafter, measurements on approximately 20 bright stars are used obtain accuracies better than 10 arc-sec. This corresponds to about 2 pixels of the image. This corresponds to about 50 m at a 1000 km range.

Table 2: Specification of COATS sensor

Parameter	Value and comments
Azimuth	-130° to +130° at 100°/s
Elevation	- 35° to +215° at 100°/s
Resolution	< 0.04 arc-sec
Accuracy	10 to 20 arc-sec (after cal, camera dependent)
Supports up to 4 optical sensors	• 3" Integrated zoom Sony camera (Zoom 0.78° to 7° FOV) • 4" Samyang mirror lens - Watec 120N camera (0.5° FOV) • 8" Richley-Chretien reflector telescope - Watec 910HX camera – filter wheel with IR pass filters (0.24° FOV) • 10" Optimised Dall-Kirkham reflector telescope - OWL 640 SWIR camera - filter wheel with IR pass filters (0.22° FOV)
Position calibration	• Auto levelling • Star calibration • Built-in GNSS and inclinometer
Tracking sources	TLE, stars, target auto-track, built-in MEP client to interface to Gandalf 25m antenna server
Acquisition and Recording	• Still images and video • Az/El look-angles

The video tracker unit on board the platform processes video, provides a video interface, performs star measurements and provides an auto-tracking function. The tracker allows the user to designate a target and switch into auto-track mode with joystick control. The tracker pulls the target onto boresight and maintains it at this position. The calibrated encoder outputs can then be used as an accurate line-of-sight measurement. Fig. 7 is a sample screen shot from the COATS video tracker screen.

Successful observations with COATS requires clear sky conditions, as well as suitable illumination of the spacecraft with the sensor in darkness. Recent investigations using an IR camera on the 8” telescope has demonstrated that observations can be extended into daylight conditions.

Fig. 7. COATS Video Tracker Screen (with SKYNET 5C)

4.5 CURUNIR CLIENT

The Curunir client was developed to connect the COATS sensor to the Chilbolton MEP network. It compromises software that is embedded in the COATS tracking platform. The client is started up with a config file option. It is normally left running and is visible to the CASTR operator through the Gandalf server screen.

4.6 SLR

The SLR (Satellite Laser Ranger) is a sensor located at the Space Geodesy Facility (SGF), near the village of Herstmonceux in East Sussex. The SGF is a research facility of the Natural Environment Research Council (NERC). The SGF makes range observations to enable orbit determination for scientific satellite missions that study the oceans, ice sheets, land mass, gravity field and climate of the Earth in order to better understand the processes at work. Fig. 8 is a picture of the SLR sensor in the dome on top of the building, and a picture of the telescopes on the tracking mount.

For support of this project, the SLR telescope was utilised in the night mode configuration for collecting astrometric and photometric data. This is a passive receive mode where the laser and the photomultiplier are not used and ranging is not conducted. Table 3 provides some basic information regarding the telescopes on the tracking mount.

Fig. 8. the SLR at NERC Space Geodesy Facility, Herstmonceux

Fig. 9 is a map of Southern England, and shows the locations of the STFC Chilbolton Observatory and NERC Space Geodesy Facility.

Table 3: Specification of SLR Telescopes

Parameter	Value and comments
Main telescope diameter	50 cm Cassegrain design
Main telescope field of view	4 arcminutes
Acquisition scope diameter	20 cm
Acquisition scope FOV	2°
Azimuth	-270° to +270° at 5°/s
Elevation	0° to 90° at 5°/s
Resolution	1-2 arcseconds (1 arcsec = 1/3600 of a degree)
Tracking sources	TLEs, CPF (consolidated prediction format) trackfiles – operator can introduce time and position offsets to get target on boresight

Fig. 9. Map of Southern England showing the locations of the STFC Chilbolton Observatory and NERC SGF sites where CASTR and the SLR are located

4.7 MITHRANDIR CLIENT

The MEP protocol was designed to accommodate the networking of sensors that were not co-located, hence to demonstrate this, an EO tracker operating at a longer baseline from the radar at the Chilbolton Observatory was required. A decision was made to try and use the SLR (satellite laser ranging) system at NERC's Space Geodesy Facility (SGF) at Herstmonceux which is 135 km from Chilbolton.

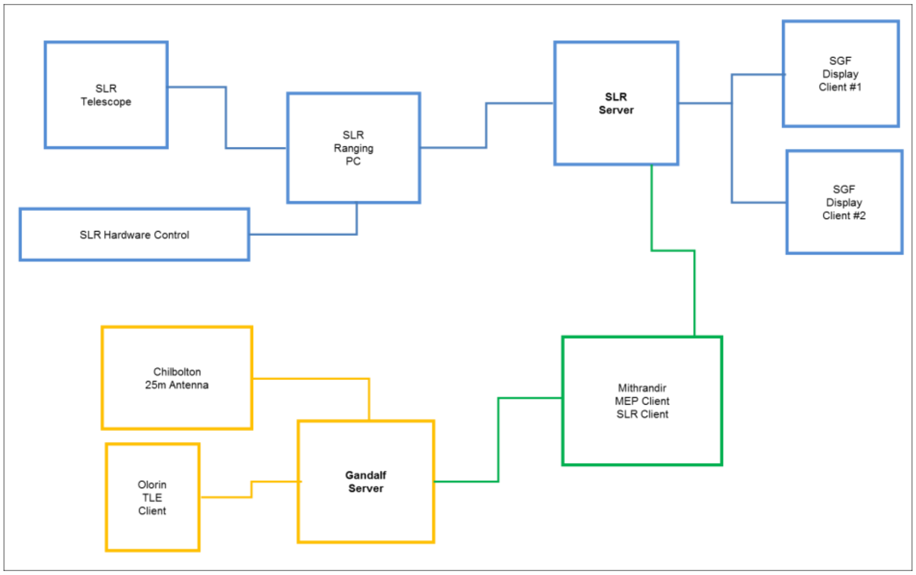

Fig. 10. Block diagram of the SGF SLR cueing network implementation

Fig. 10 is a block diagram that illustrates the stages involved in the supply of the SLR position data through the Mithrandir client to slave the 25m antenna pointing. The SLR server sends the position data to the connected clients, including the Mithrandir client at 10 Hz. The position data being sent out are not the precise pointing angles of the telescope because the data have been corrected for atmospheric refraction and represent the precise location of the object being tracked.   The Mithrandir client sends position updates to the Gandalf server at 10 Hz. This information can be displayed on the local (Herstmonceux) screen (Fig. 11) as well at the remote (Chilbolton) screen and it reflects the live pointing of the telescope to satellites. All data is propagated with UTC time stamps which originate from the SLR ranging PC. Corrections added to the telescope pointing are included in the updates. Filters are used correct for the latencies which occur during the data transfer.

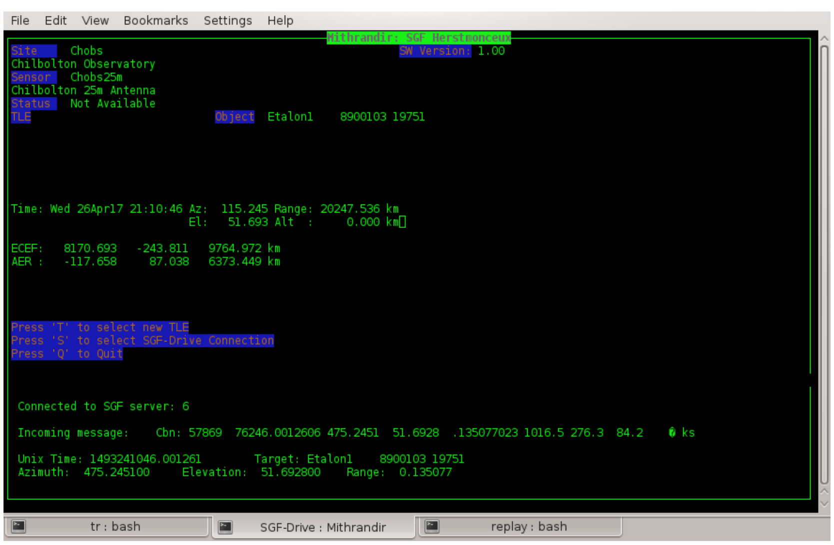

Fig. 11. Mithrandir client display

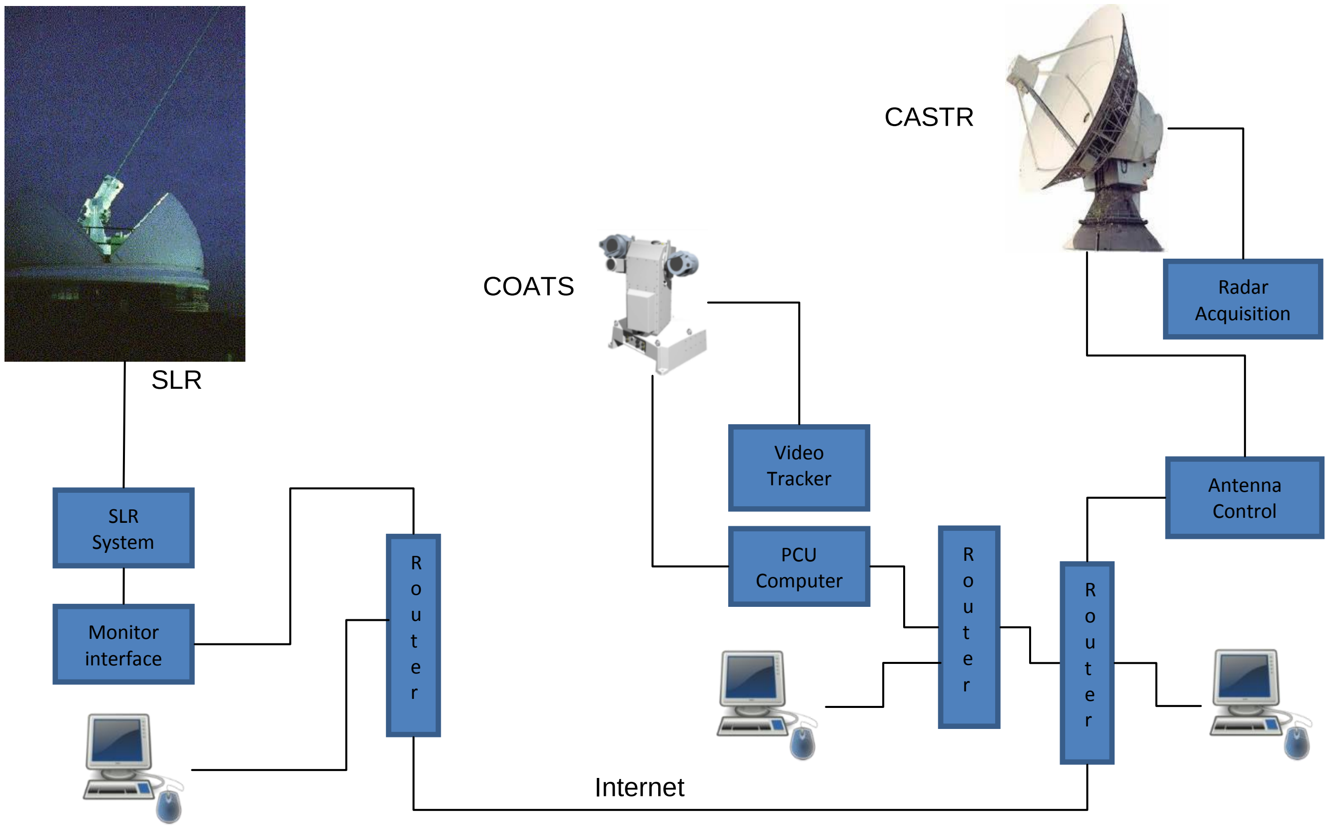

Fig. 12. Chilbolton MEP network

5. GANDALF LATENCY AND TIME DIFFERENCE CONSIDERATIONS

There are number of sources of latency and time differences that affect the pointing accuracy when the 25 m antenna when it is controlled by a remote sensor. The processing within Gandalf aims to minimise these effects. The end-to-end sources involved between the SLR at Herstmonceux and Chilbolton are estimated in Table 4.

Table 4: Gandalf latency and time differences

	Source	**Typical Magnitude**
1	SLR image capture and Mithrandir client time delay	Unknown
2	Mithrandir to Gandalf network delay	low ms
3	Mithrandir and Gandalf synchronisation	0 to 100 ms
4	Station time difference	Unknown
5	Gandalf internal synchronisation delay	0 to 20 ms
6	Gandalf to 25 m antenna controller	210 ms
7	25 m antenna controller to Gandalf	20 ms
8	Gandalf output (at 10 Hz)	0 to 100 ms
9	Gandalf to Mithrandir network delay	low ms

The latency of data from the input to Mithrandir, to Gandalf and on to the antenna controller system is compensated with Gandalf by the two sets of prediction code.

The latency from the antenna controller to Gandalf is also compensated within the Gandalf code by adjusting the time stamp of the incoming data. This compensated time stamp is used for all display data and any outgoing data to the clients.

All MEP clients poll the server to get information on the server's clock and network latency. Likewise Gandalf polls all connected clients to get information on their clocks and network latency. Currently this information is logged for post event analysis.

Site time synchronisation is usually achieved using NTP with either public NTP servers or more precise GPS or atomic clock conditioned servers. NTP over public networks can maintain synchronisation errors to be less than 100 ms, whereas use of a local GPS or atomic clock can maintain errors less than a few milliseconds. In view of this, it is highly recommended that sensor sites use a local GPS or atomic clock.

6. TESTING AND RESULTS

Initial testing of the MEP protocol and the client/server architecture was conducted in March 2016. It was done initially using the Olorin TLE client running locally on the same machine as the Gandalf server. The sensor protocol worked effectively, and the antenna was accurately pointed at a variety of targets in LEO, which was ascertained by successful detection and measurement of the range.

Follow on testing involved collaborative tracking of a number of objects with both CASTR and COATS. The following procedure was followed:

1. CASTR and COATS independently tracked a common object using the same TLE.
2. COATS was switched into auto-track of the object, and the target was brought onto boresight.
3. The COATS client was selected on the Gandalf server, and control of CASTR switched to using look-angles being streamed through the MEP system.

Transition between TLE and EO was generally smooth, depending on the error in the TLE and the amount the antenna had to move. In all situations the object was maintained in the beam when the COATS was auto-tracking, however, COATS had difficulty auto-tracking targets for which the illumination was too variable.

6.1 OPERATOR TWEAKS ON A NOMINAL TLE TRACK

During observations made on 11th April 2017, CASTR was slaved to the SLR during a track of the ISS (International Space Station). CASTR was initially cued onto the ISS track using the Olorin TLE client and the latest available ISS TLE. The SLR was also using the same TLE to cue the SLR, but once the target was in the telescope field of view, time and position offsets were used to centre it on the telescope boresight.

Recording of the radar data started when the antenna was on TLE track. Once the SLR operator had introduced time and position tweaks to centre the ISS on the boresight, the CASTR slaving was transferred to the SLR feed. It is apparent in the plot of radar signal strength versus time in Fig. 13 below that there is a notable jump in the signal level at 19:37:10 when the antenna has been slaved to the SLR pointing. There is a brief drop in the signal between 19:37:07 and 19:37:10 while the antenna settles on the new track. The signal increase between the two segments was 7.4 dB.

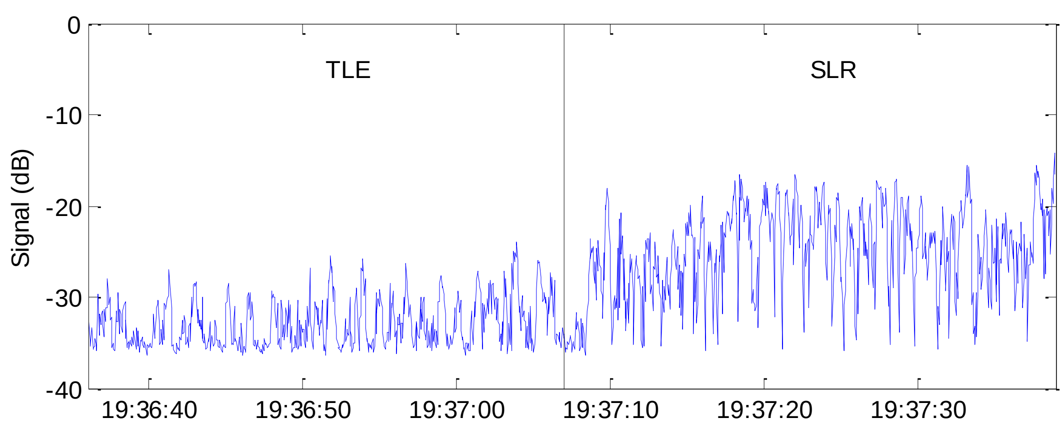

Fig. 13. Comparison of radar signal strength of ISS between TLE tracking and SLR tracking

6.2 OPERATOR TWEAKS ON A POOR TLE TRACK

In the above example, the nominal TLE was accurate enough for both the radar and the EO sensor to immediately detect the target. However, there have been events where the radar has not seen a tracked target because the TLE does not predict the track of the object accurately enough to place it within the beamwidth of the antenna (0.27^{o}). This has even happened when tracking the ISS despite its large size because there has been a spacecraft manoeuvre since the release of the TLE.

It was decided for observations on 18th April, to use a poor TLE in order to test the ability to bring CASTR onto the track of an object for which the TLE wasn't accurate enough. A suitable poor TLE would be one for which the object had recently been manoeuvred, or the object was in late stages of an uncooperative re-entry and the orbit was changing quickly.

During the observations on the evening of 18th April 2017, ENVISAT was tracked using a TLE that was 38 days old (from 9th March 2017, instead of 16th April 2017). Both the SLR and CASTR used the old TLE to cue the sensors. Once the satellite was above the horizon, and the SLR operator had brought it onto boresight, the 25m antenna was slaved to the SLR, and the target was immediately detected.

Later investigation revealed that the peak return from the ENVISAT pass was nearly 10 dB greater than any of the peaks observed in ENVISAT passes of the preceding year.

6.3 SENSOR DATA COMPARISON

The plots in Fig. 14 below show coordinated CASTR radar and SLR optical data from an ENVISAT pass collected 21st March 2017. The plot on the left shows the relative magnitudes after de-trending. Clearly, there are peaks in the radar data and similar peaks in the SLR data, although they are not exactly synchronous. This timing difference is most likely caused by the different look angle from the two observation sites, illumination direction and frequency.

The plot on the right shows the autocorrelation plots of the two different sensor signals. The autocorrelation plots indicate different periodic rates determined for the two sensors.

ENVISAT is tumbling which creates peaks on both the radar returns and optical photometry. There have been several papers and reports [3, 4, 5] indicating that the tumble period of ENVISAT is increasing. At the end of 2015 it was approximately 195 s. Extrapolating to the beginning of 2017 gives a period of 230 s. At the time of the measurements, a period of between 250 s and 280 s was estimated. The peaks are more frequent than the published tumbled rate, but that can be explained as the target having multiple reflections from different faces as it spins.

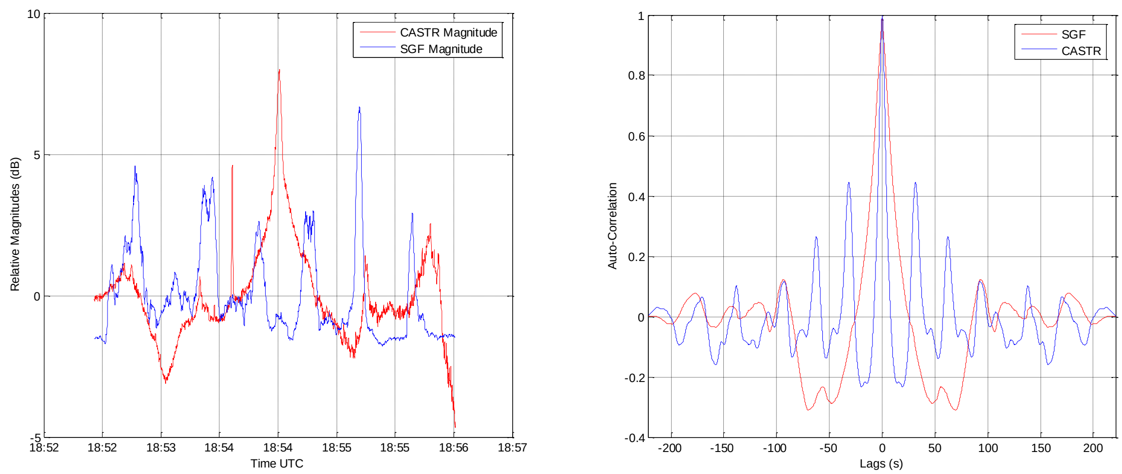

Fig. 14. Comparison of radar and optical signals (left) and autocorrelation of optical and radar signals (right)

7. SUMMARY

The MEP network has enabled slaving the CASTR 25m antenna to two different auto-tracked optical sensors. This has allowed the radar to successfully detect satellites without it relying on accurate ephemerides to point the antenna at the targets. Reliance on an optical sensor does constrict when it can be used, but the fusion of the coordinated data sets can produce interesting results.

This activity has yielded some good results. The trials conducted with CASTR slaved to the SLR telescope have shown significant benefit to enabling CASTR to detect objects where a TLE is not accurate enough to get the target within the beam, and also to improve the target return over what a nominal TLE can achieve. Conducting further trials will allow better characterisation of when this technique will yield significant improvements.

Future work includes addition of more sensors on extended baselines, as well as implementation of additional servers to enable more cueing/slaving opportunities.

8. REFERENCES

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